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Chiou et al.

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(54) **3D STACKED PIEZORESISTIVE PRESSURE SENSOR**

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G01L 7/08 (2006.01)
G01L 9/00 (2006.01)
(Continued)

(52) **U.S. Cl.**
CPC .... ***G01L 9/0052*** (2013.01); ***B81B 7/00*** (2013.01); ***G01L 9/0042*** (2013.01); (Continued)

(58) **Field of Classification Search**
CPC ..... G01L 7/00; G01L 7/08; G01L 9/00; G01L 9/0042; G01L 9/0055; G01L 9/06; (Continued)

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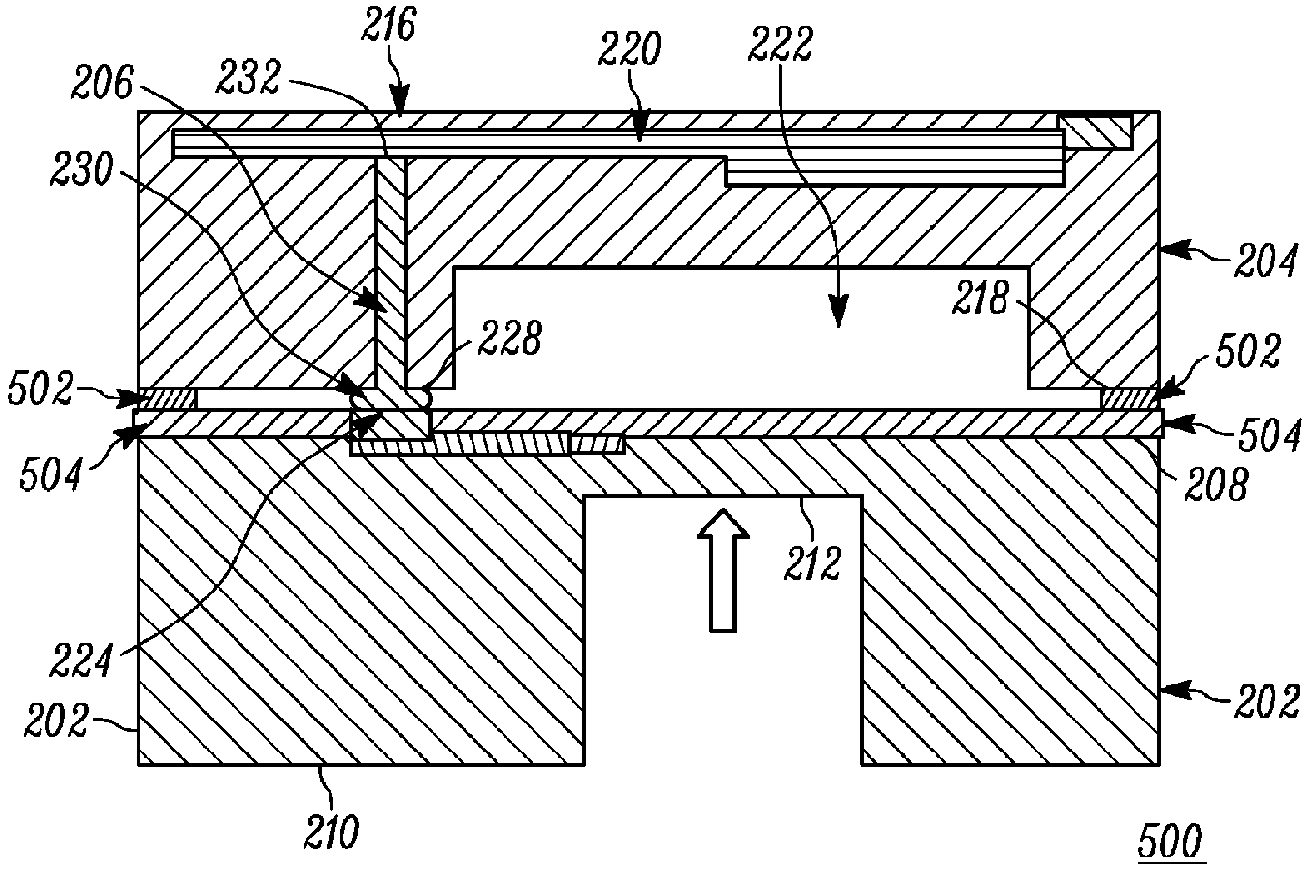
Primary Examiner — Nguyen Ha

(57) **ABSTRACT**

In a microelectromechanical system (MEMS) pressure sensor, thin and fragile bond wires that are used in the prior art to connect a MEMS pressure sensing element to an application specific integrated circuit (ASIC) for the input and output signals between these two chips are replaced by stacking the ASIC on the MEMS pressure sensing element and connecting each other using conductive vias formed in the ASIC. Gel used to protect the bond wires, ASIC and MEMS pressure sensing element can be eliminated if bond wires are no longer used. Stacking the ASIC on the MEMS pressure sensing element and connecting them using conductive vias enables a reduction in the size and cost of a housing in which the devices are placed and protected.

28 Claims, 15 Drawing Sheets



(51) **Int. Cl.**
G01L 9/06 (2006.01)
G01L 19/00 (2006.01)
G01L 19/14 (2006.01)
B81B 7/00 (2006.01)

(52) **U.S. Cl.**
CPC ***G01L 9/0055*** (2013.01); ***G01L 9/06*** (2013.01); ***G01L 19/0076*** (2013.01); ***G01L 19/0084*** (2013.01)

(58) **Field of Classification Search**
CPC . G01L 19/00; G01L 19/0076; G01L 19/0084; G01L 19/14; B81B 7/00
See application file for complete search history.

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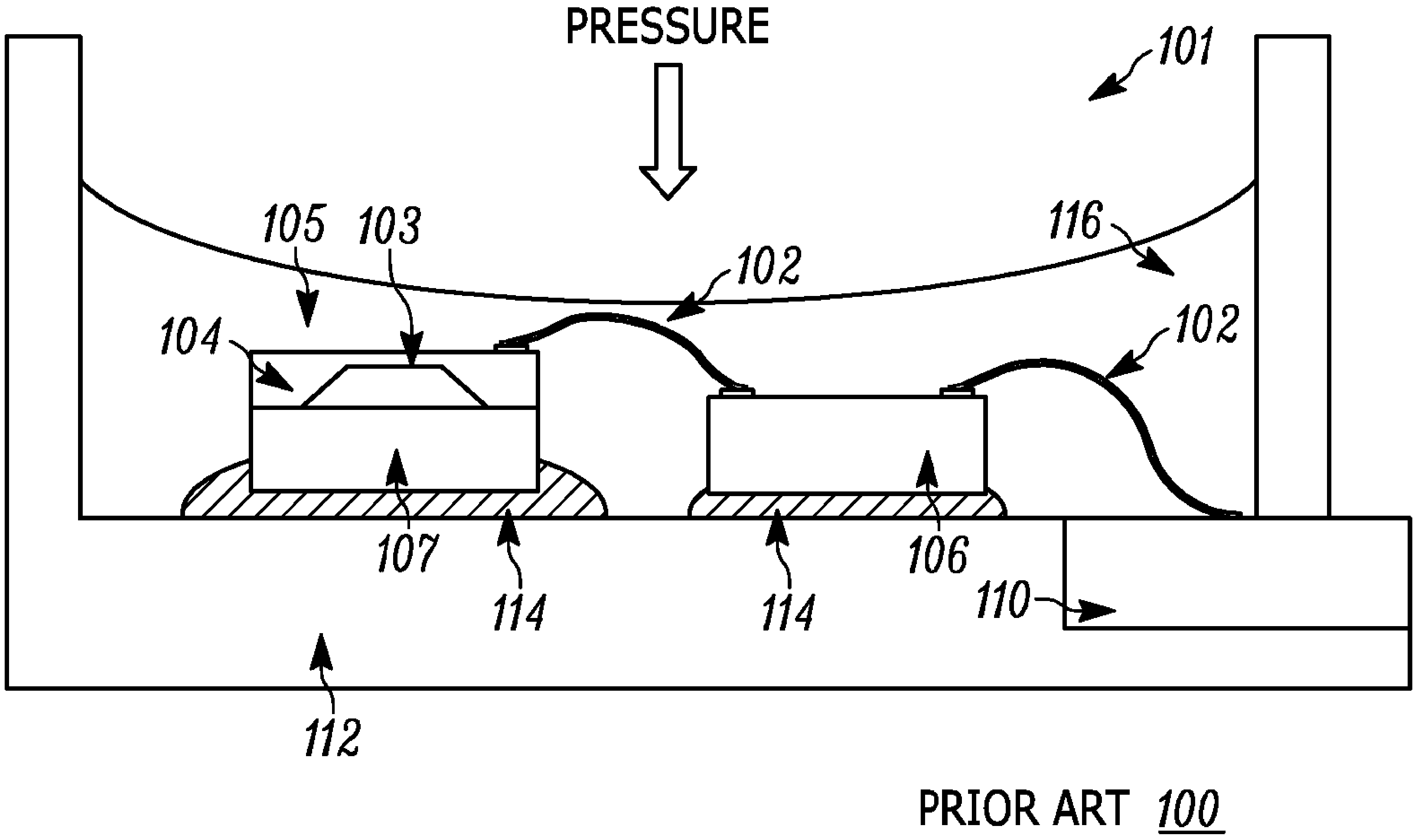

PRESSURE
101
105
103
116
102
104
102
107
114
114
106
110
112
PRIOR ART 100

FIG. 1

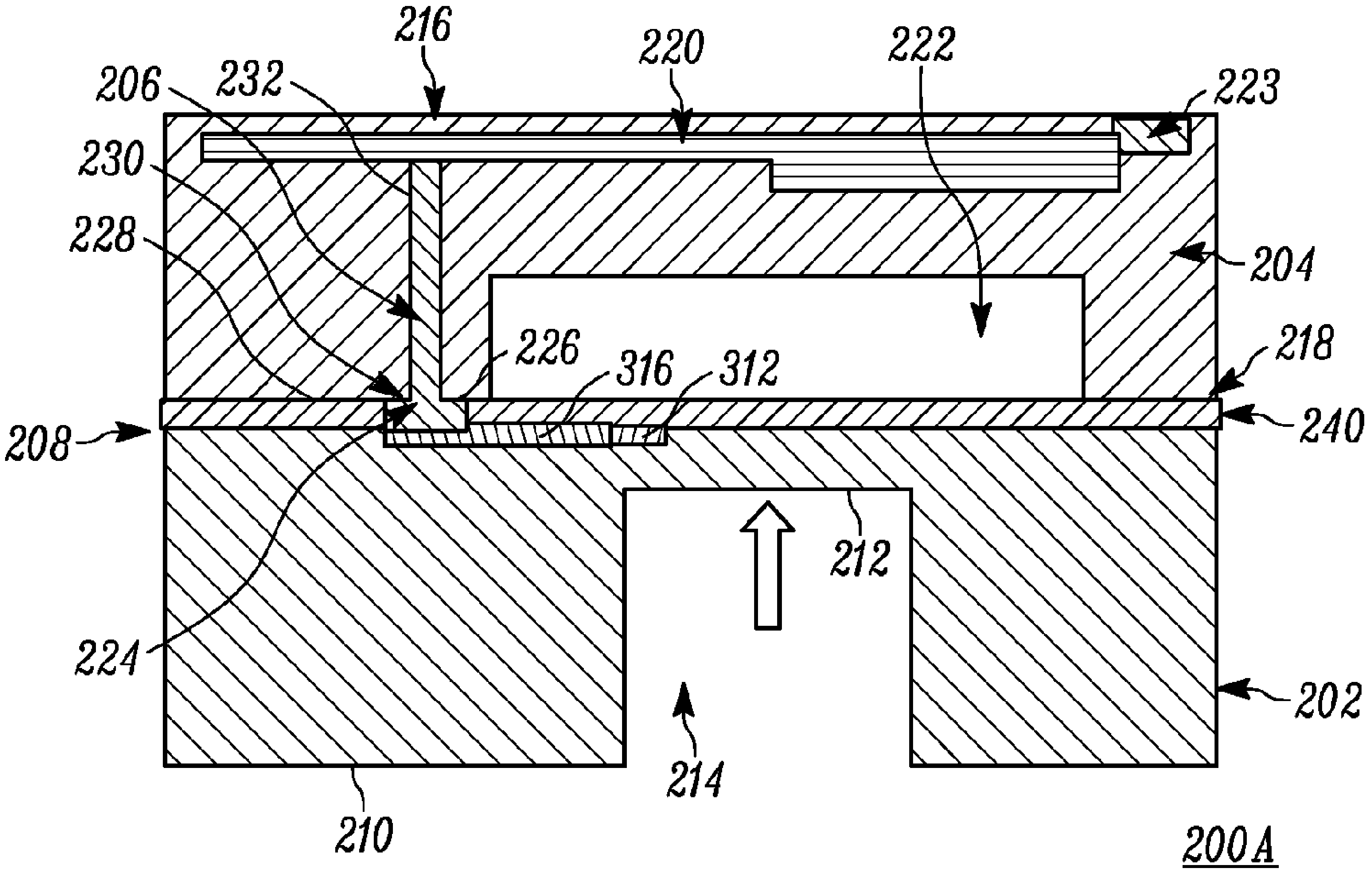
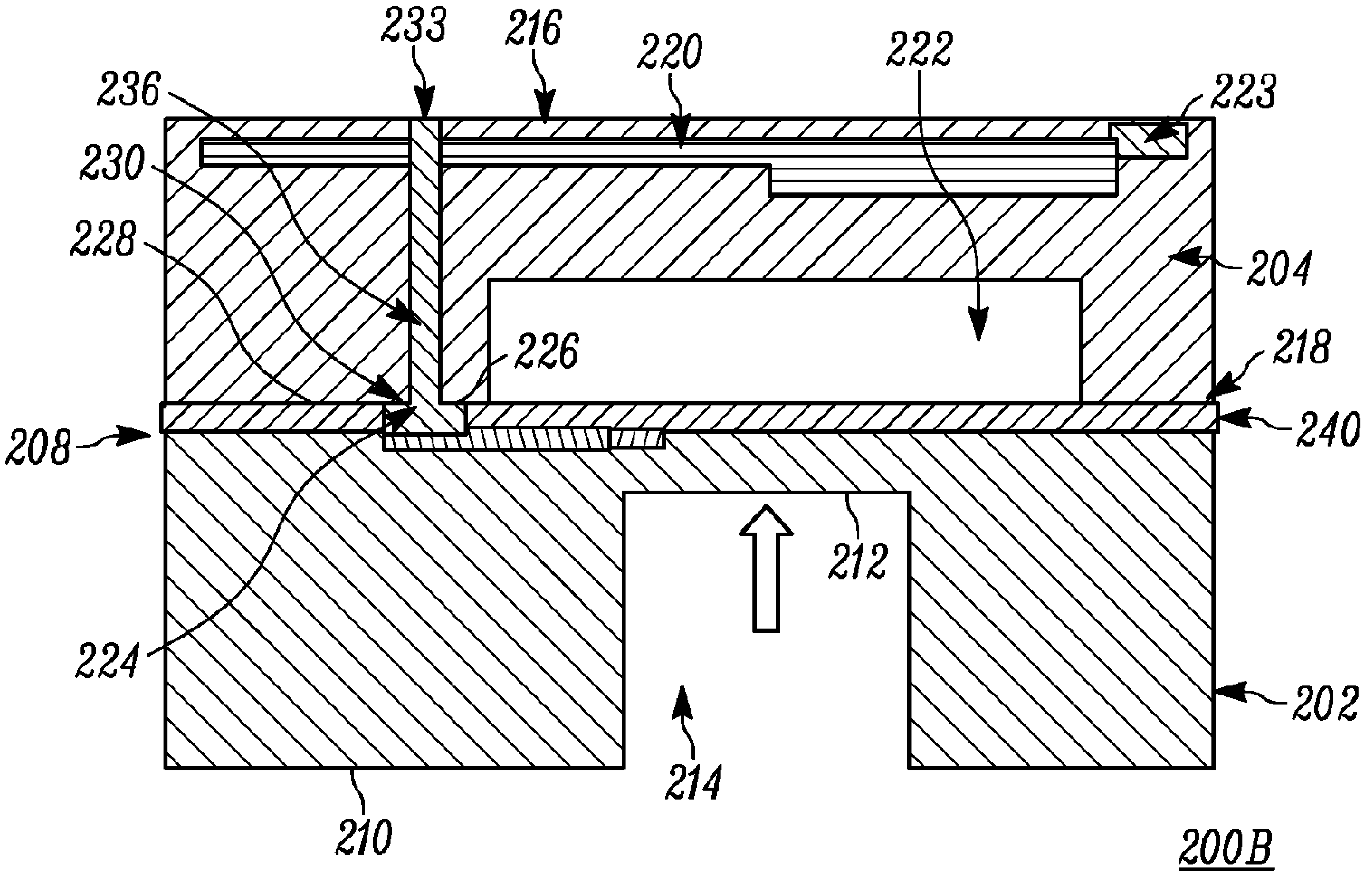

216
220
222
223
206
232
230
228
204
226
316
312
218
208
240
212
224
202
214
210
200A

FIG. 2A


233
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236
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204
226
218
208
240
212
224
202
214
210
200B

FIG. 2B

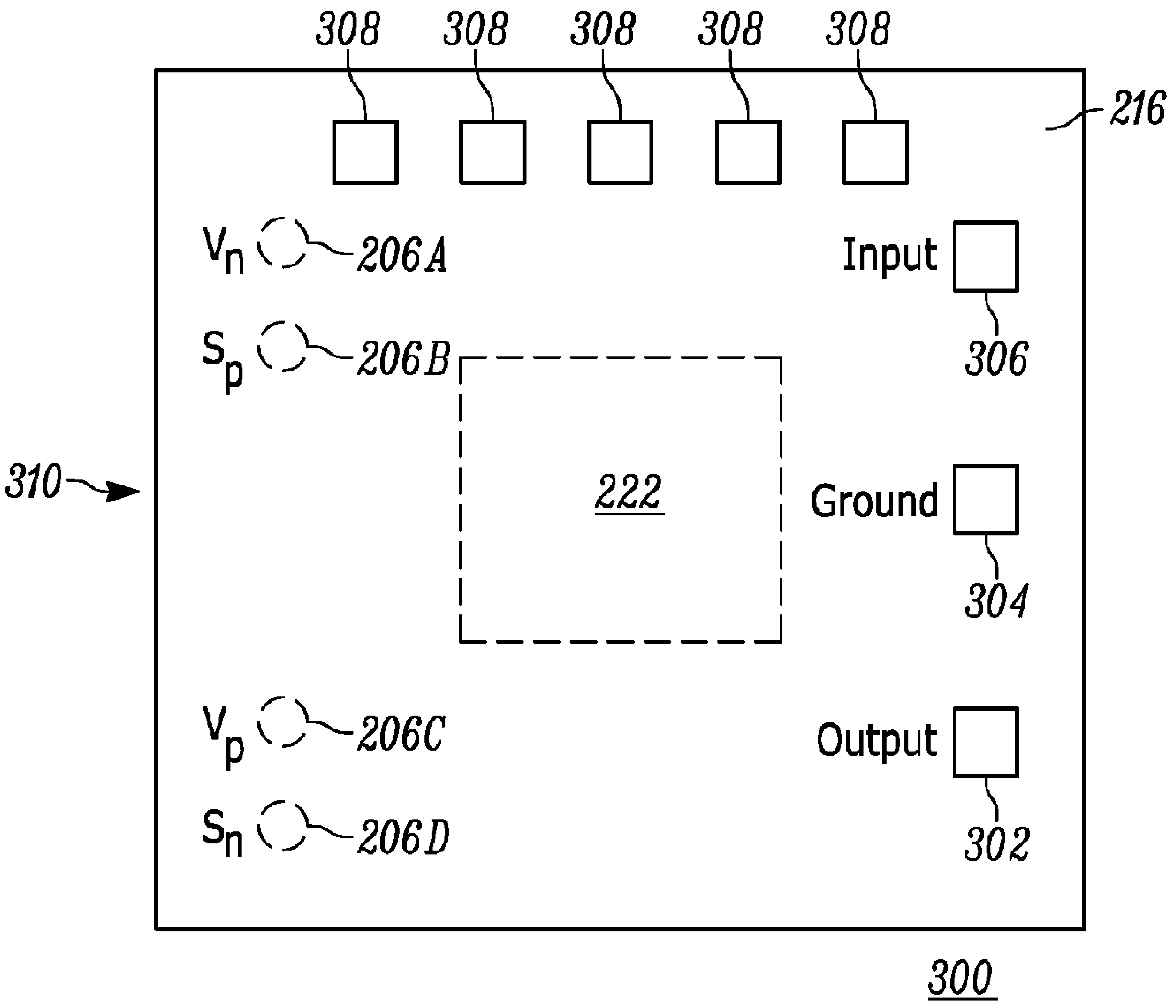

308
308
308
308
308
216
V_n
206A
Input
306
S_p
206B
310
222
Ground
304
V_p
206C
Output
302
S_n
206D
300

FIG. 3

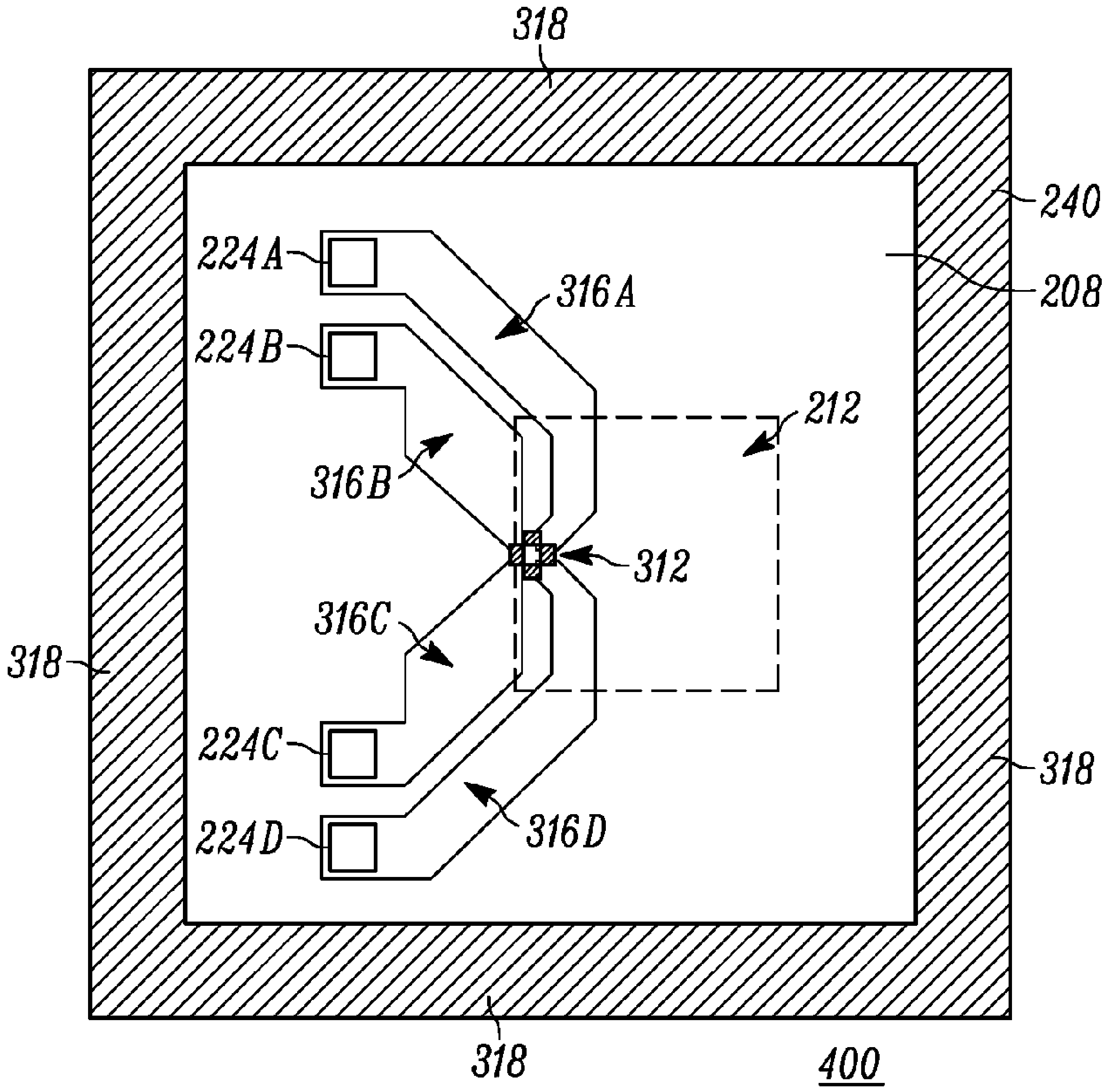

318
240
208
224A
316A
224B
212
316B
312
316C
318
318
224C
224D
316D
318
400

FIG. 4

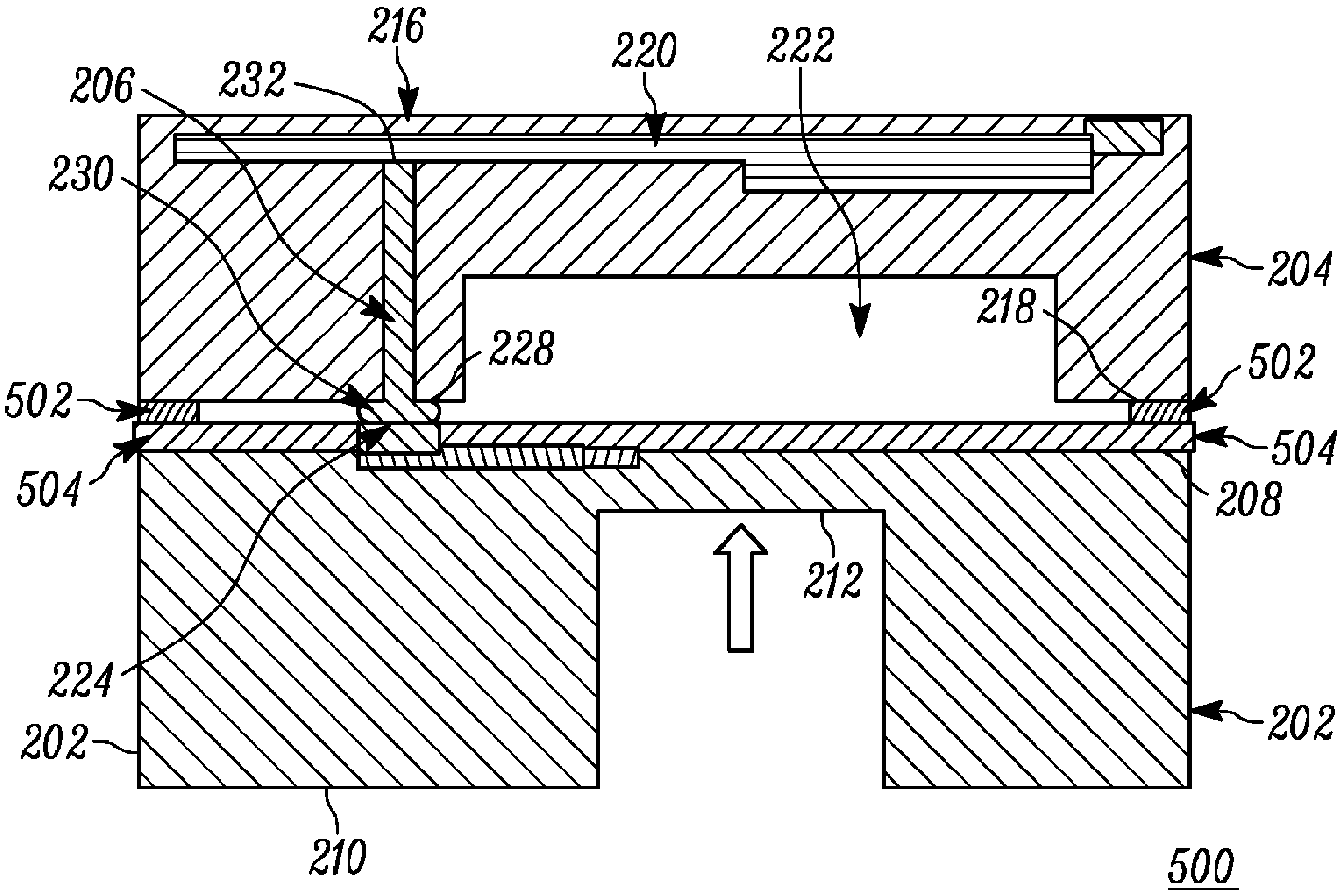
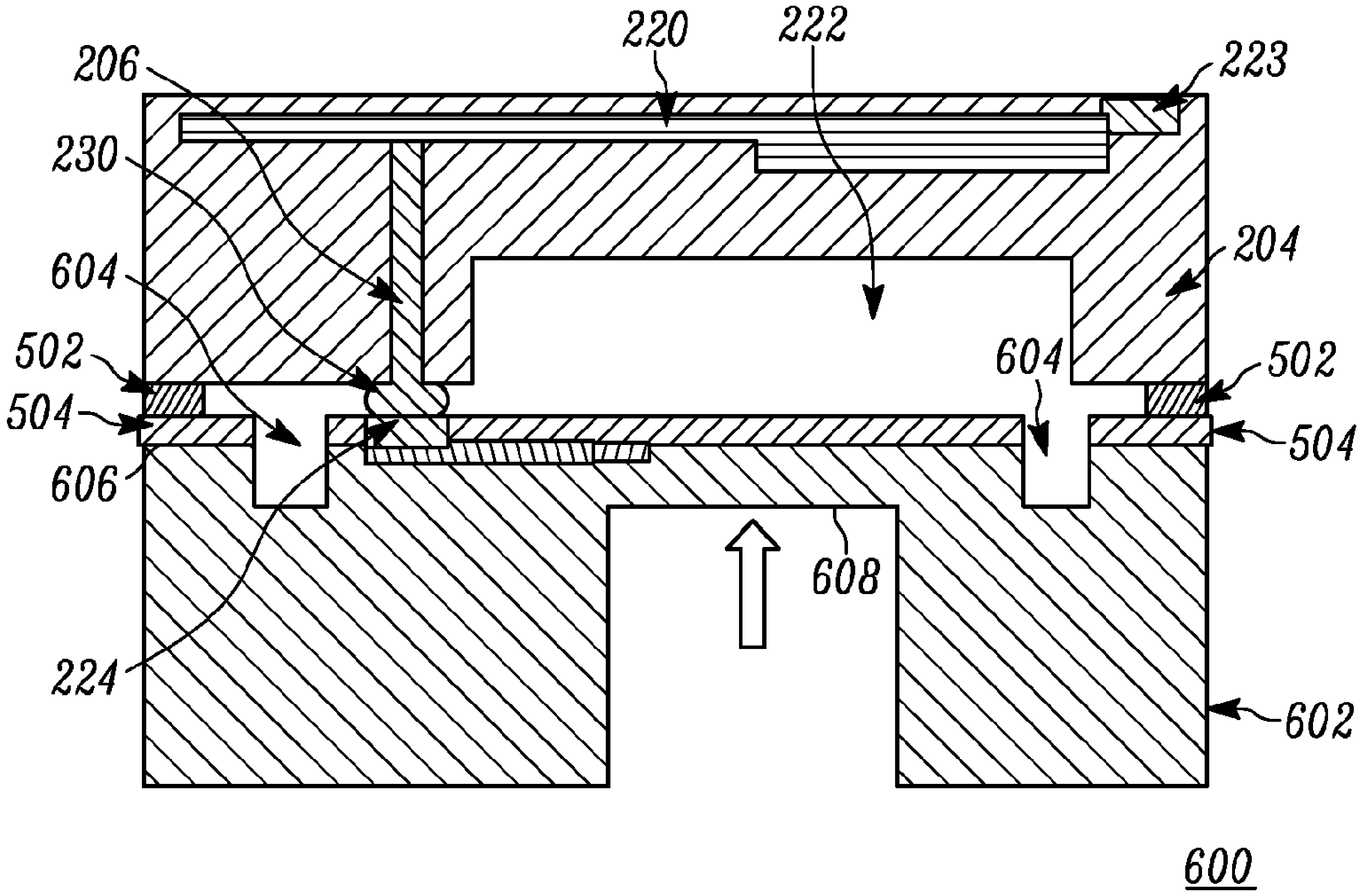

216
206
232
220
222
230
204
228
218
502
502
504
504
208
212
224
202
202
210
500

FIG. 5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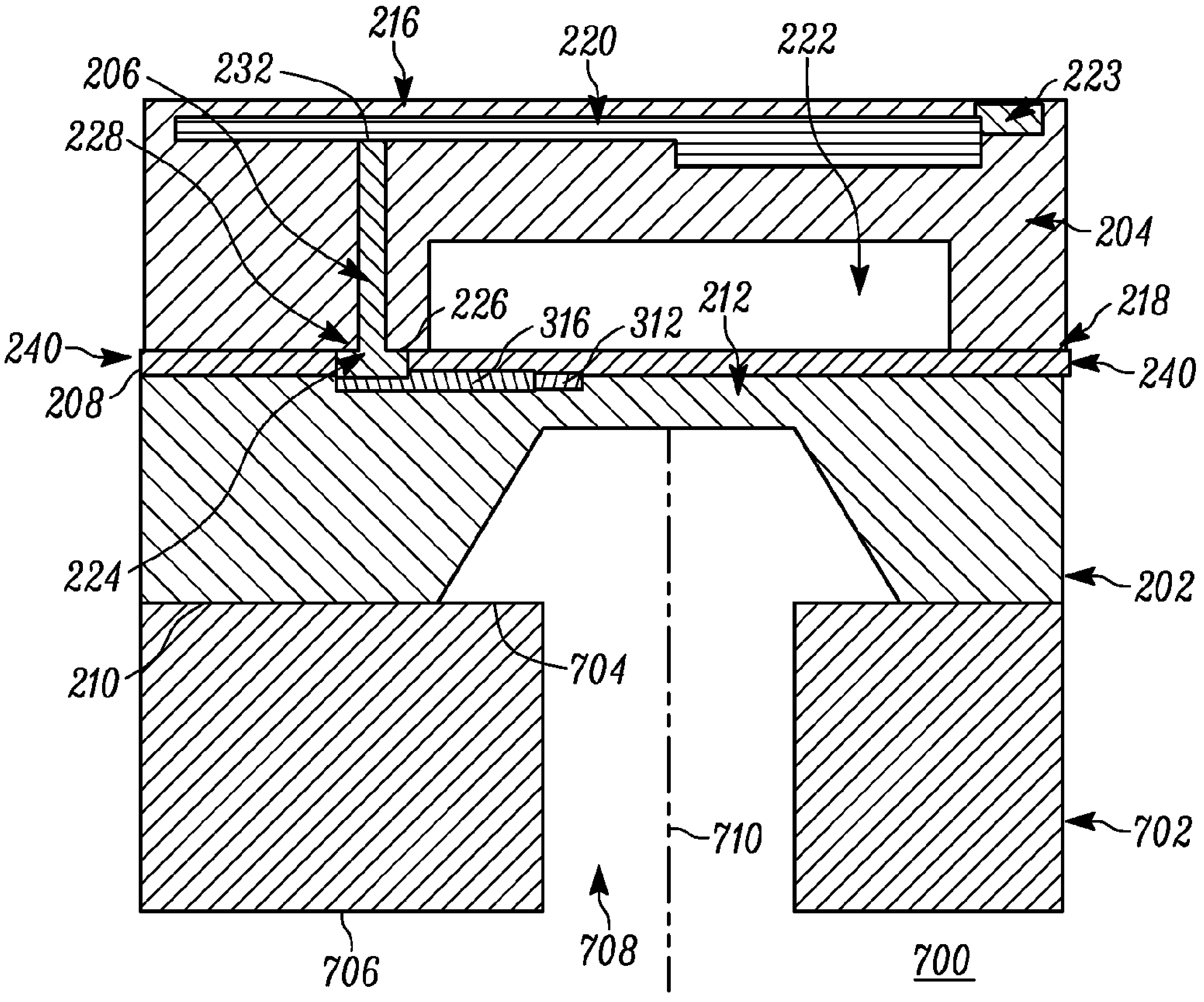
222
223
206
230
204
604
604
502
502
504
504
606
608
224
602
600

FIG. 6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206
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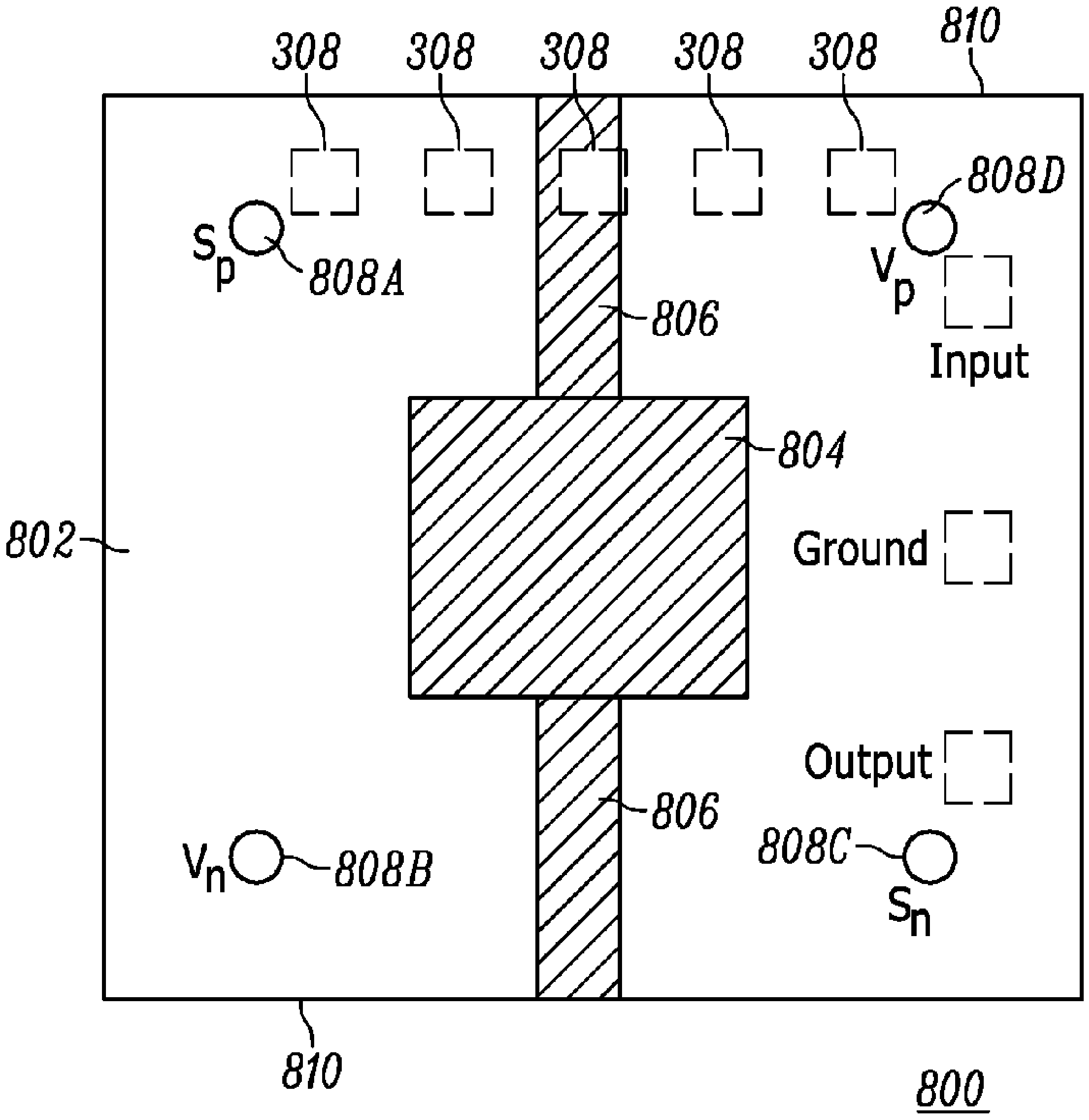
208
224
202
210
704
710
702
706
708
700

FIG. 7


308
308
308
308
308
810
808D
S_p
808A
V_p
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Input
804
802
Ground
Output
806
V_n
808B
808C
S_n
810
800

FIG. 8A

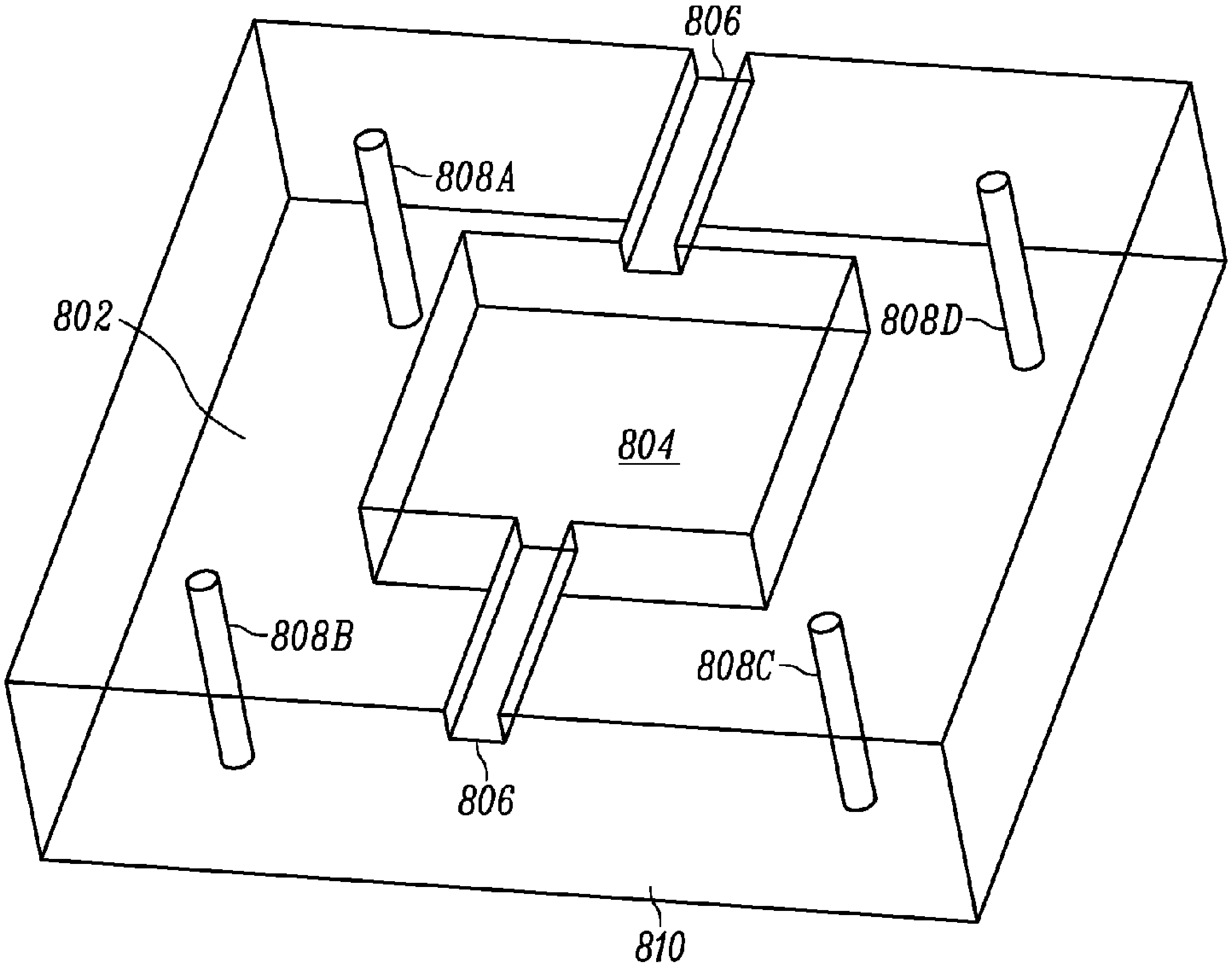
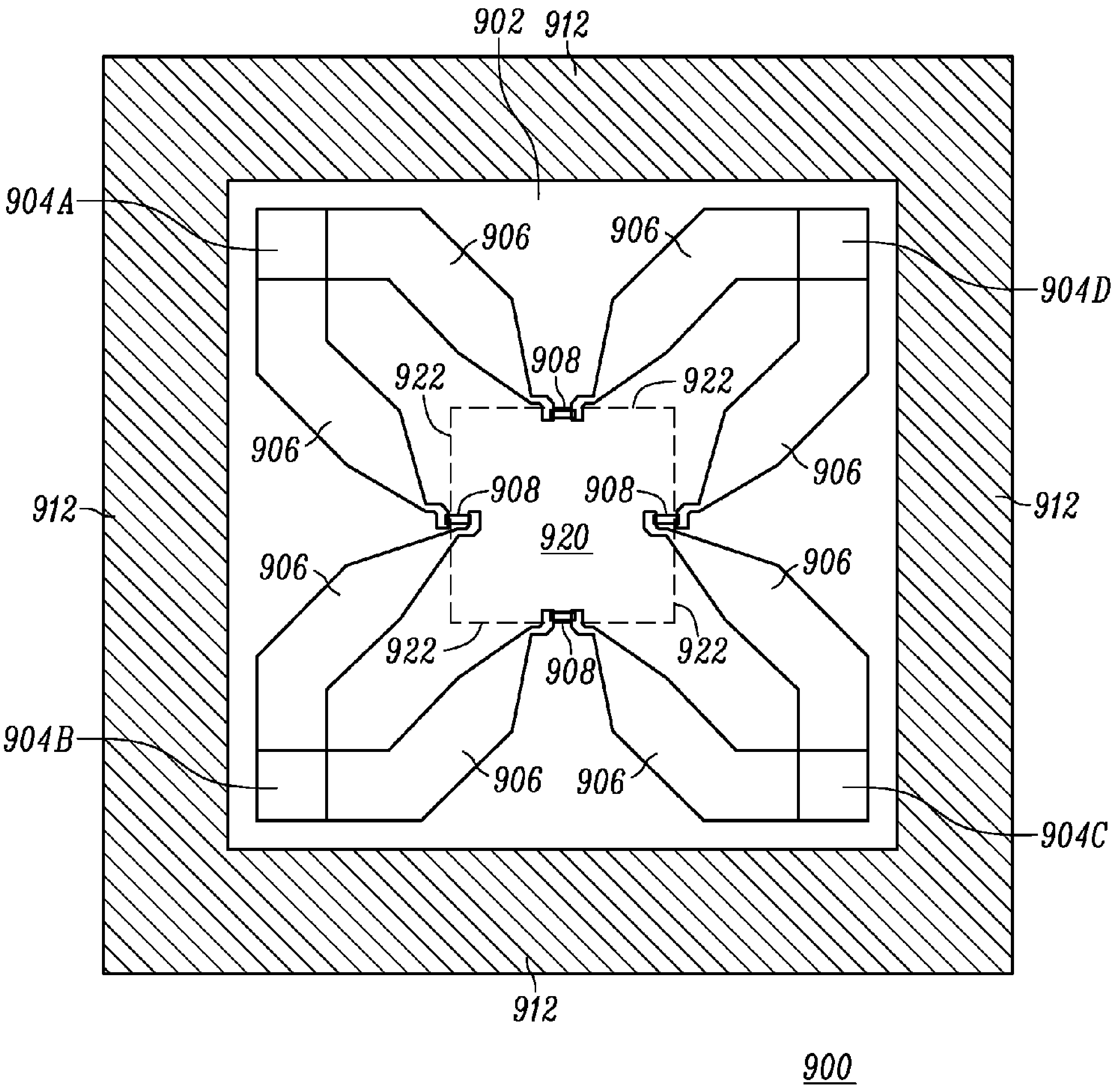

806
808A
802
808D
804
808B
808C
806
810

FIG. 8B


902
912
904A
906
906
904D
908
922
922
906
906
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912
920
906
906
922
922
908
904B
906
906
904C
912
900

FIG. 9

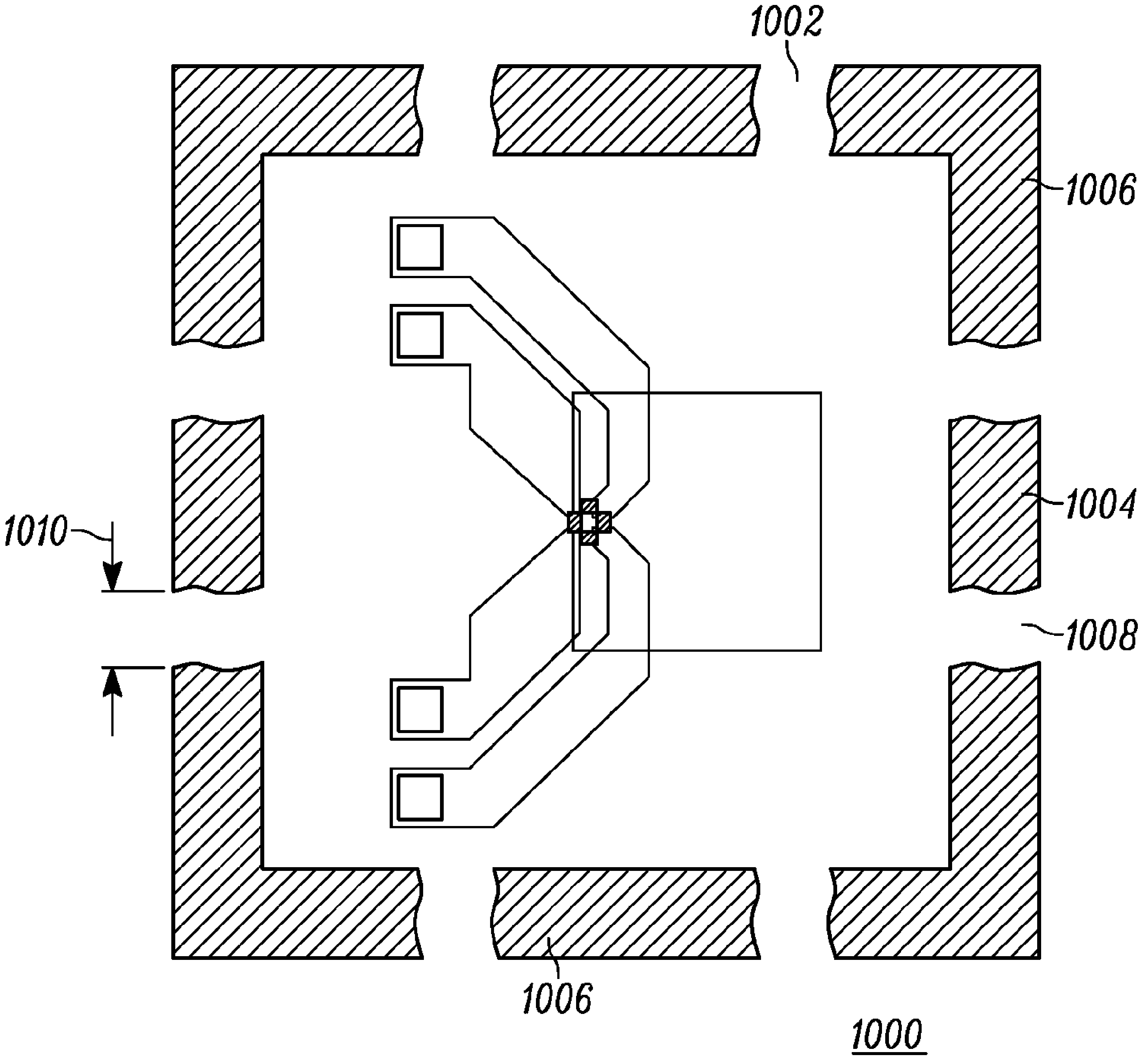


FIG. 10

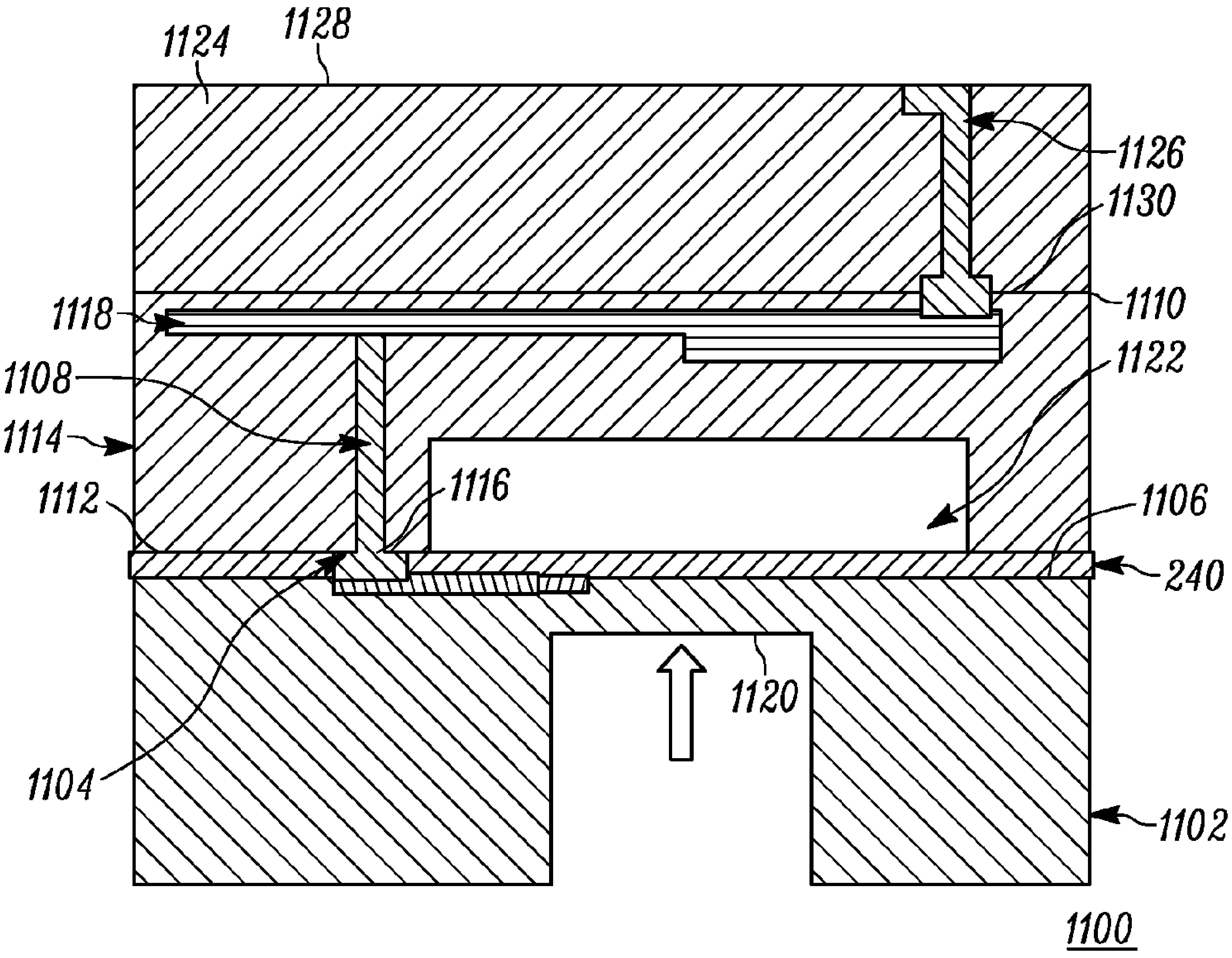

1124
1128
1126
1130
1110
1118
1122
1108
1114
1116
1112
1106
240
1120
1104
1102
1100

FIG. 11

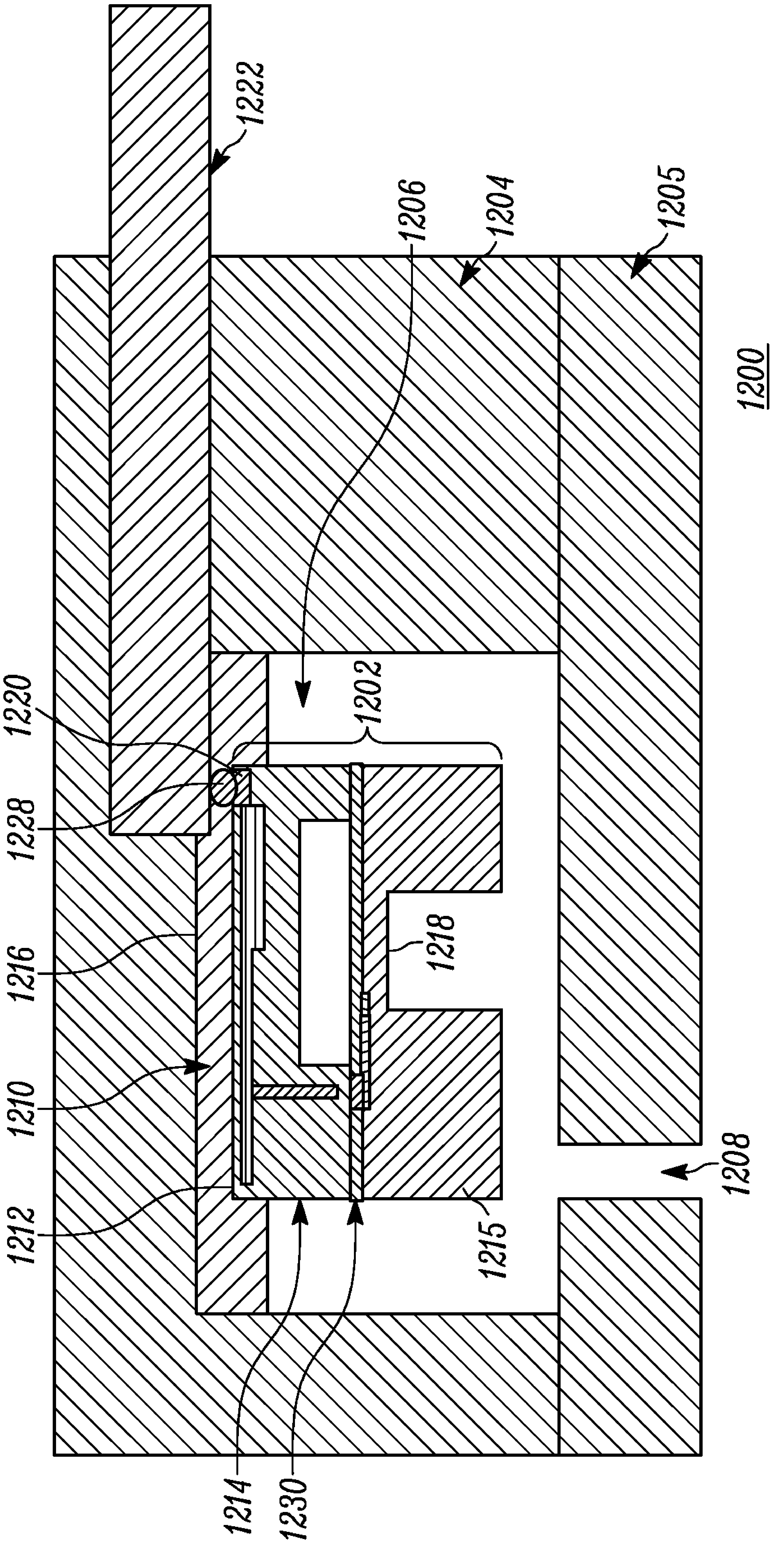
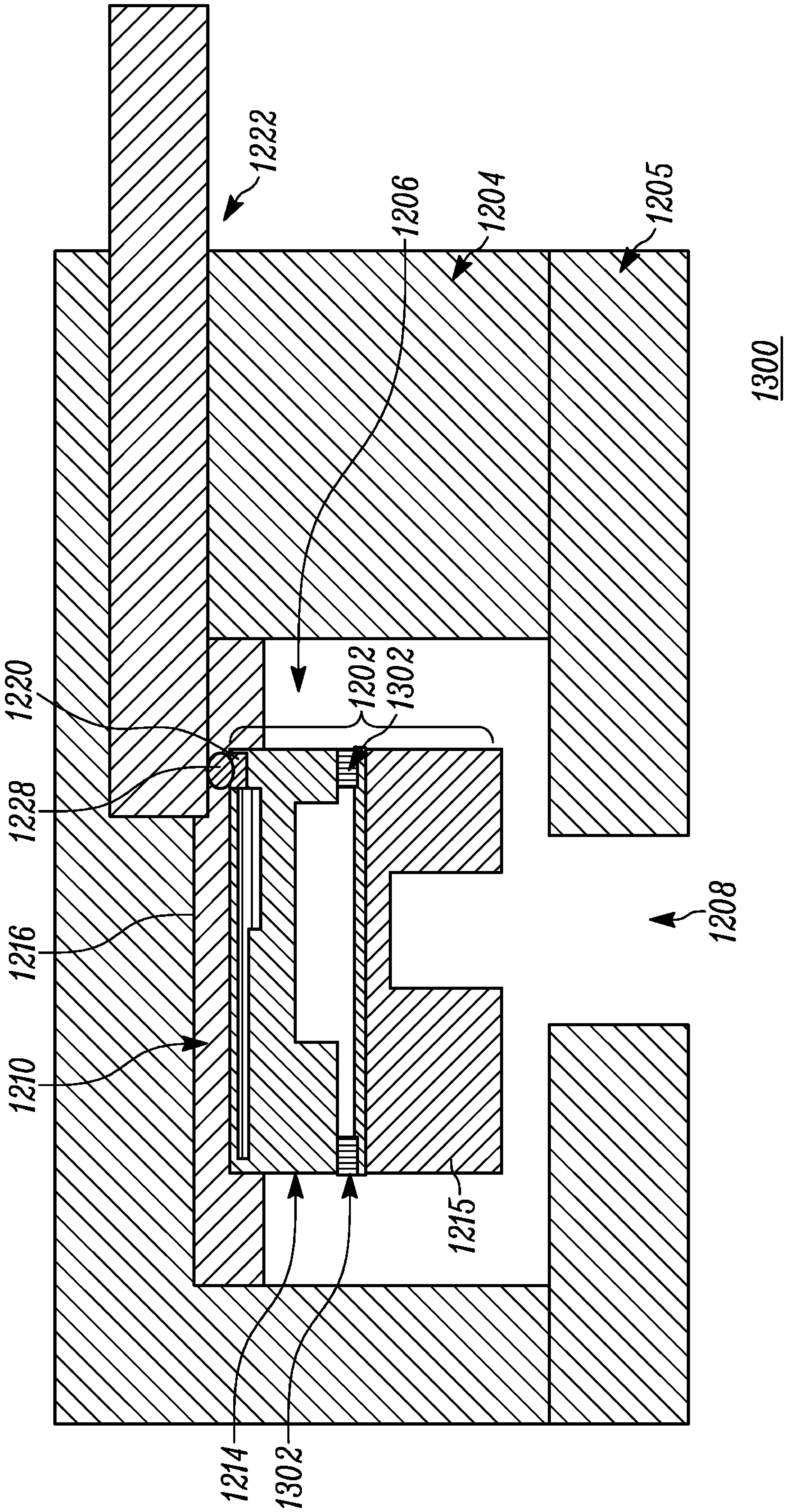

1222
1206
1204
1205
1200
1202
1220
1228
1216
1210
1212
1218
1208
1215
1214
1230

FIG. 12


1222
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1204
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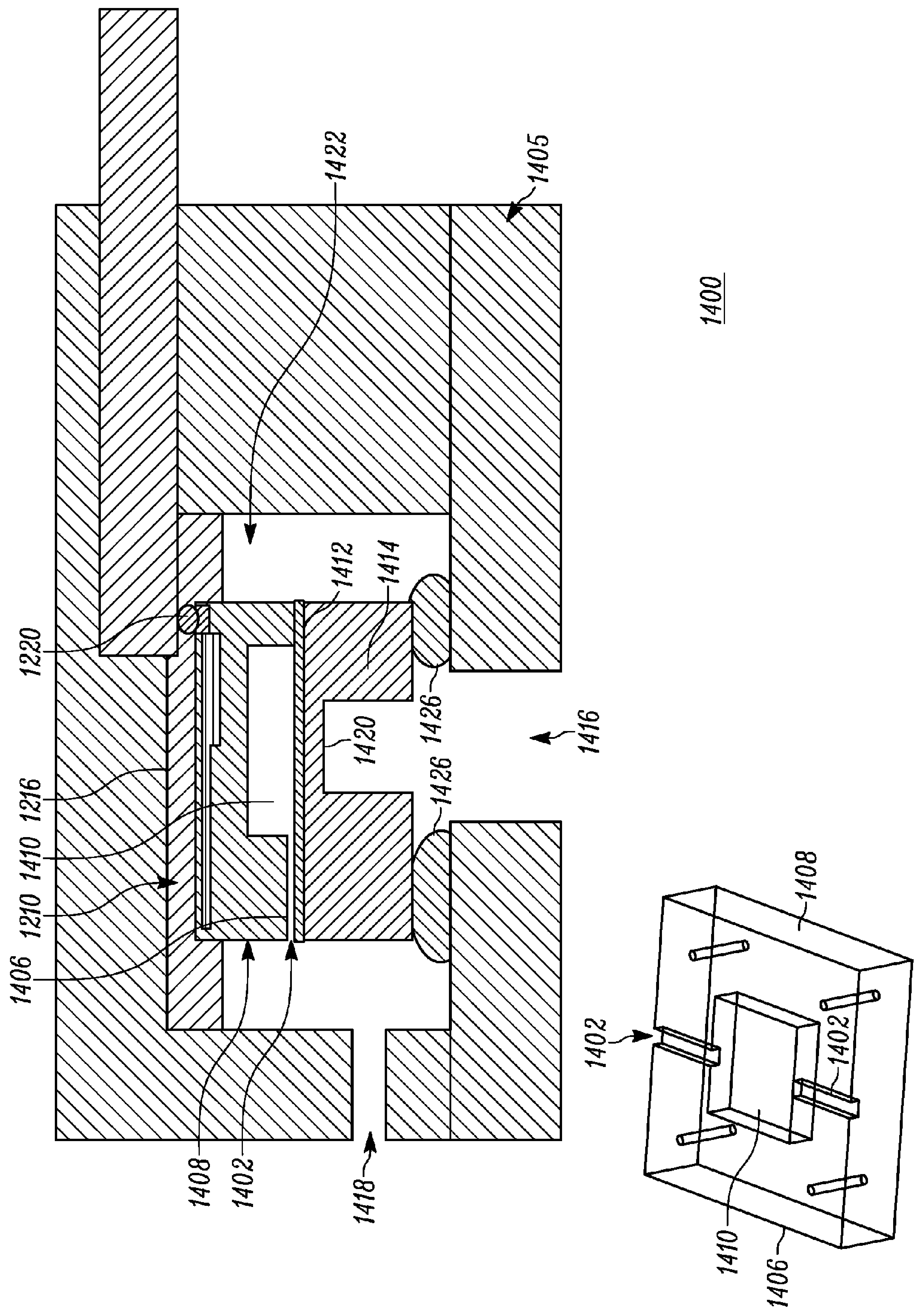
1300
1202
1302
1220
1228
1216
1210
1208
1215
1214
1302

FIG. 13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1220
1216
1410
1210
1406
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1426
1416
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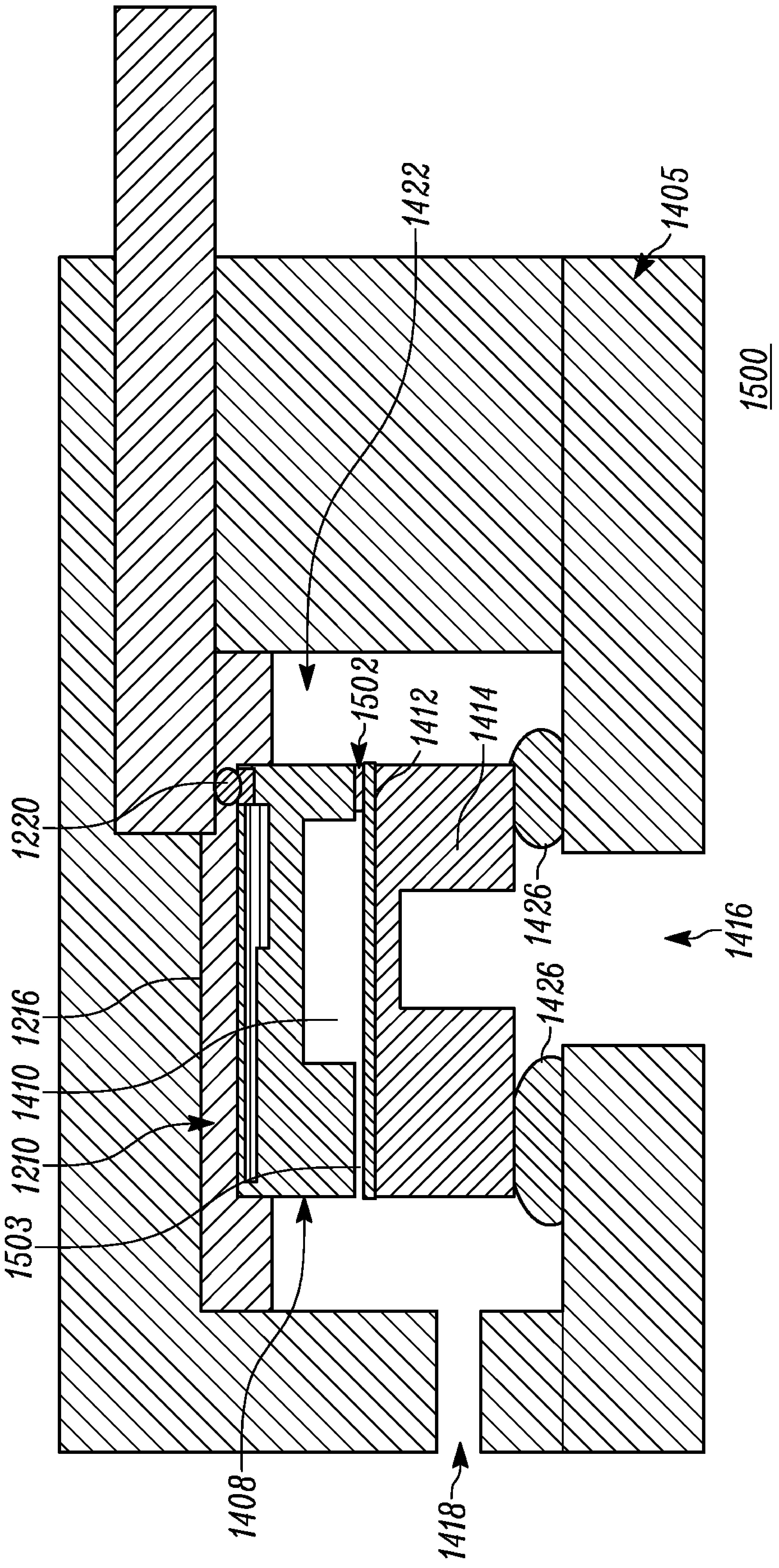
1418
1408
1402
1402
1410
1406

FIG. 14


1500
1405
1422
1502
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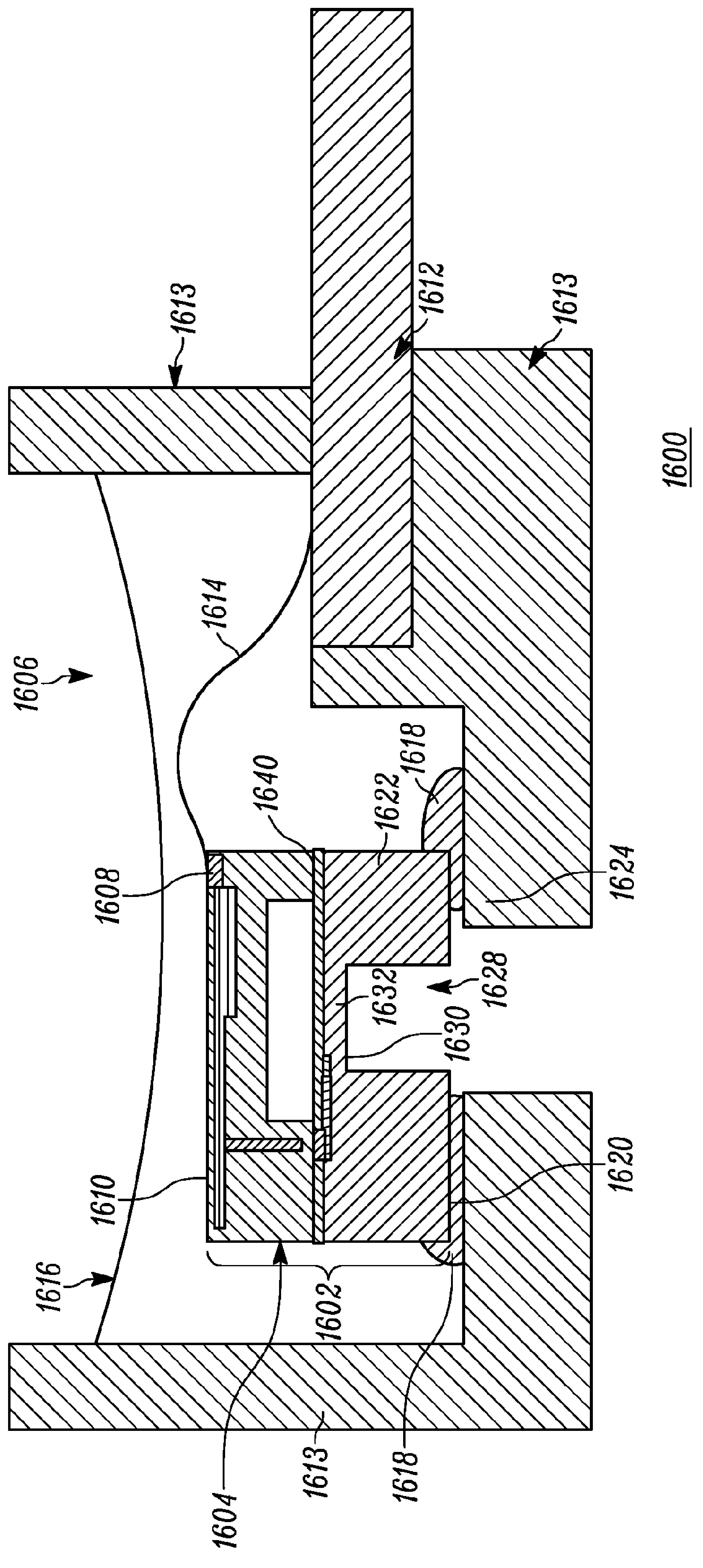
1414
1220
1426
1426
1416
1216
1410
1210
1503
1408
1418

FIG. 15


1613
1612
1613
1600
1606
1614
1640
1622
1618
1608
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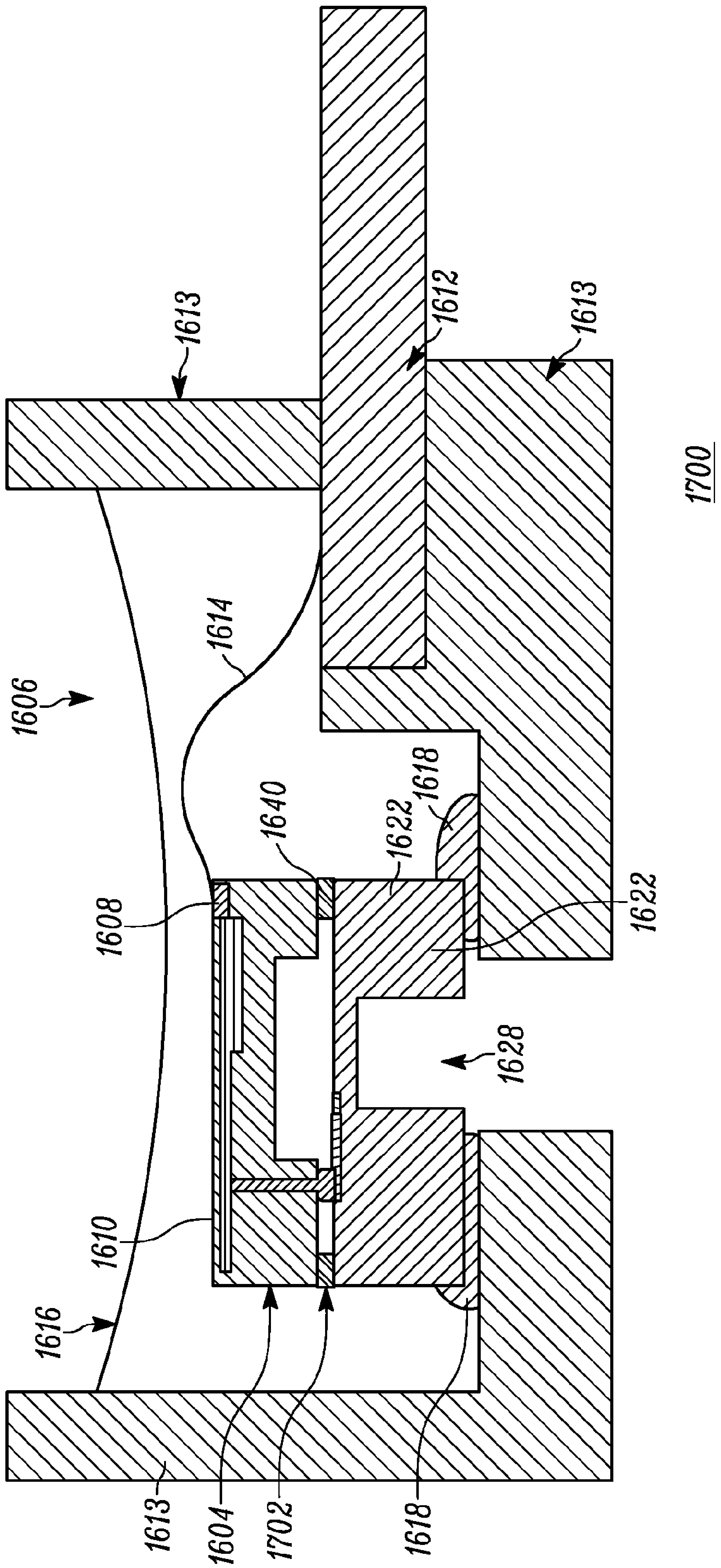
1632
1628
1630
1610
1620
1616
1602
1604
1613
1618

FIG. 16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1612
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1700
1606
1614
1640
1622
1618
1608
1622
1628
1610
1616
1613
1604
1702
1618

FIG. 17

3D STACKED PIEZORESISTIVE PRESSURE SENSOR

BACKGROUND

FIG. **1** is a cross-sectional view of a prior art MEMS piezoresistive pressure sensor module **100**. It provides excellent pressure measurements for a wide range of fluids across a wide range of low pressures.

The pressure sensor module comprises essentially two dies, one is a MEMS pressure sensing element **104** and the other is an application specific integrated circuit (ASIC) identified by reference numeral **106**. A vacuum cavity **103** is formed between a diaphragm **105** and a substrate **107** in the pressure sensing element **104**. When pressure is applied on the diaphragm **105**, the diaphragm **105** deflects and creates stresses on a Wheatstone bridge (not shown) on the diaphragm and converts the diaphragm deflection into a measurable voltage change. The two dies **104** and **106** are mounted to a housing substrate **112** using an adhesive **114**. Small-diameter bond wires **102** extend and connect between the MEMS pressure sensing element **104** and the ASIC **106**. The bond wires **102** also extend and connect between the ASIC **106** and a lead frame **110**.

The wires **102** add cost and are of course susceptible to failure. Eliminating wires that extend between the MEMS pressure sensing element **104** and the ASIC **106** and between the ASIC **106** and the lead frame **110** would reduce cost and improve the reliability of the MEMS pressure sensing element and MEMS pressure sensors.

A viscous gel **116** inside a pocket **101** protects the pressure sensing element **104**, the ASIC **106**, and the bond wires **102** from pressurized media, the pressure of which is to be measured. The gel **116** needs to be soft enough in order to transmit pressure. The gel **116** on the top of the diaphragm **105**, however, can cause a power-on voltage shift of the signals output from the device if high charges are stored in the gel. The gel **116** can also affect sensing accuracy in a severe vibration environment because of its mass. The gel **116** is expensive especially in a large pocket with two separated dies or chips **104** and **106**. Reducing the pocket size, eliminating the gel and bond wires, or at least reducing gel quantity, or replacing expensive gel by less expensive gel for lower cost and better performance, would be an improvement over the prior art.

SUMMARY OF THE INVENTION

The protective gel and bond wires can be eliminated and the size of a pocket holding a pressure sensor device can be significantly reduced by stacking an application specific integrated circuit (ASIC) with a cavity on top of a MEMS pressure sensing element. The ASIC and pressure sensing element are electrically connected to each other using conductive vias formed into the ASIC.

BRIEF DESCRIPTION OF THE FIGURES

FIG. **1** depicts a prior art topside absolute pressure sensing element inside a pocket, which is connected to an application specific integrated circuit (ASIC) by bond wires;

FIG. **2**A is a cross-sectional view of a first embodiment of a backside pressure sensor device comprising a MEMS pressure sensing element and an ASIC, which are coupled to each other with conductive vias that extend through the backside of the ASIC;

FIG. **2**B is a cross-sectional view of a second embodiment of a backside pressure sensor device comprising a MEMS pressure sensing element and an ASIC, which are coupled to each other with conductive vias that extend completely through the backside of ASIC with circuitry formed in the topside of the ASIC;

FIG. **3** depicts a first or top side of the ASIC depicted in FIGS. **2**A and **2**B and shows in broken lines, the relative locations of conductive vias that extend through the backside of ASIC and metal bond pads on the topside;

FIG. **4** depicts the first or top side of the MEMS pressure sensing element and metal bond pads or terminals, which are aligned with and mate with the vias in FIG. **3**;

FIG. **5** is a cross-sectional view of a third embodiment of a pressure sensor device comprising a MEMS pressure sensing element and an ASIC, which are coupled to each other by glass frit and solder bumps with conductive vias that extend through the backside of the ASIC;

FIG. **6** is a cross-sectional view of a fourth embodiment of a pressure sensor device comprising groove on the topside of a MEMS pressure sensing element of the third embodiment shown in FIG. **5**;

FIG. **7** is a cross-sectional view of the first embodiment of a pressure sensor device with a pedestal mounted onto the backside of a MEMS pressure sensing element;

FIG. **8**A is a plan view of the second or bottom side of an ASIC and that depicts a recess and trenches on the second or bottom side of the ASIC, exposed ends of conductive vias that mate with corresponding bond pads on a MEMS pressure sensing element;

FIG. **8**B is a perspective view of the second or bottom side of ASIC depicted in FIG. **8**A;

FIG. **9** depicts the first or top side of a MEMS pressure sensing element with metal bond pads that mate with the vias shown in FIG. **8**A and depicting a bonding area either by fusion or glass frit bond around the perimeter of the first or top side;

FIG. **10** depicts the first or top side of a MEMS pressure sensing element with metal bond pads that mate with the vias shown in FIG. **8**A and a patterned layer of glass frit, the glass frit pattern providing openings through which a monitored fluid can pass;

FIG. **11** depicts an alternate embodiment of a pressure sensor device having two integrated circuits stacked on top of a MEMS pressure sensing element;

FIG. **12** depicts a first embodiment of a backside absolute pressure sensor module comprising a backside absolute pressure sensor device as shown in at least FIG. **2**A, a housing in which the pressure sensor device is located and a lead frame, which extends through the housing and having a fusion bond between the ASIC and the MEMS pressure sensing element;

FIG. **13** depicts a second embodiment of a backside absolute pressure sensor module, which has a glass frit bond between the ASIC and the MEMS pressure sensing element;

FIG. **14** depicts a cross section of a differential pressure sensor module having a fusion bond between the ASIC and the MEMS pressure sensing element;

FIG. **15** depicts a cross section of a second embodiment of a pressure sensor module having a patterned glass frit bond between the ASIC and MEMS pressure sensing element;

FIG. **16** depicts a cross section of a pressure sensor module comprising a backside absolute pressure sensor device formed by fusion bond, such as the one shown in at least FIGS. **2**A and **2**B, the ASIC metallic bond pads of which are connected to lead frames using bond wires that are protected by a viscous gel; and

FIG. **17** is a cross section of an alternate embodiment of a backside absolute pressure sensor module as shown in FIG. **16**, formed by a patterned glass frit bond.

DETAILED DESCRIPTION

The I.E.E.E. Standards Dictionary, Copyright 2009 by the IEEE, defines "via" as a physical connection between two different levels of interconnect, or between a level of interconnect and a physical or logical pin. As used herein, a via is a vertical or substantially vertical column of conductive material formed into a substrate having opposing top and bottom or first and second sides. A via can extend all the way through a substrate, i.e., between and through opposing top and bottom/first and second sides but as shown in the accompany figures it can also extend only part way through a substrate. A via provides a vertically-oriented conductive pathway through or part way through a semiconductor substrate.

As used herein, the term "bond pad" refers to the conductive areas commonly found on an ASIC or a MEMS pressure sensing element of the prior art. The term should not, however, be construed as limited to conductive areas used in the prior art but should instead be more broadly construed to include any size conductive area on a surface of either an ASIC or a MEMS pressure sensing element, to which an electrical connection can be made.

Thin bond wires, which in prior art pressure sensor devices extend between bond pads on an ASIC and bond pads on a MEMS pressure sensing element are eliminated by vertically stacking the ASIC on top of a MEMS pressure sensing element. The two devices are connected electrically using vias formed into the ASIC and located to align with bond pads on the MEMS pressure sensing element. The vias are positioned or located in ASIC substrate so that when the ASIC is placed on a MEMS pressure sensing element, the vias align with bond pads on the MEMS pressure sensing element to which prior art bond wires would be attached.

FIG. **2A** is a cross-sectional view of a first embodiment of a backside absolute pressure sensor device **200** comprising a microelectromechanical system (MEMS) pressure sensing element **202** on top of which is an application specific integrated circuit (ASIC) **204**. The MEMS pressure sensing element **202** is similar to the MEMS pressure sensing element described in U.S. Pat. No. 8,215,176 and U.S. Pat. No. 8,466,523. Both prior art patents also disclose an ASIC, which both patents describe as being connected to a MEMS pressure sensing element using bond wires. Both patents are incorporated herein by reference in their entirety.

The MEMS pressure sensing element **202** has a top side **208** and an opposing bottom side **210**. The top side **208** includes a flexible diaphragm **212**. The diaphragm **212** deflects upwardly and downwardly responsive to pressure and/or vacuum applied to the diaphragm **212** through a pressure port **214** formed into the bottom **210** of the element **202**.

As shown in FIG. **4**, a Wheatstone bridge circuit is formed on the topside **208** of the MEMS pressure sensing element **202** by four P-doped piezoresistors **312** near an edge **314** of the diaphragm **212** and four interconnects **316**A-**316**D. The four piezoresistors **312** are electrically connected to the metal bond pads **224**A-**224**D by the four interconnects **316**A-**316**D, which are P+ doped localized regions of the top side **208**. The Wheatstone bridge circuit shown in FIG. **4**, is called a picture-frame Wheatstone bridge (PFWB) or a localized Wheatstone bridge (LWB).

A different type of Wheatstone bridge circuit is depicted in FIG. **9** with each piezoresistor **908** doped and located near each associated diaphragm edge **922** on the top side of a diaphragm **920**. This type of Wheatstone bridge circuit is called a distributed Wheatstone bridge (DWB).

As with the MEMS pressure sensing element, the ASIC **204** has a top side **216** and an opposing bottom side **218**. Passive and active electronic devices that comprise a circuit **220** are formed into the top side **216** by conventional integrated processing techniques well known to those of ordinary skill in the integrated circuit art.

Unlike the ASICs used in prior art, the ASIC **204** shown in FIG. **2A** has a bottom or second side **218**, which is formed to have a recess **222**, which is a hollowed-out space formed into the bottom or second side **218**. When the ASIC **204** having a recess **222** is attached to a MEMS pressure sensing element **202** in a vacuum or near vacuum, the recess **222** becomes or defines an evacuated cavity **222** that is directly above the diaphragm **212**. Being evacuated, the cavity **222** does not exert force on the diaphragm **212** facilitating its deflection responsive to pressure of a fluid in a pressure cavity **214**.

As shown in FIG. **2A**, the metal bond pads **224** of the MEMS pressure sensing element **202** are located directly below conductive vias **206** that extend from the bottom side **218** of the ASIC **204** to electronic circuitry formed in the top side **216** of the ASIC. An electrical connection between the bond pads **224** on the top surface **208** of the MEMS pressure sensing element **202** and the bottom end **228** of a conductive via **206** is assured by an intermetallic bond pad **230** that is attached to the bottom end **228** of a conductive via **206** on the bottom or second side of the ASIC **204**. The top end **232** of the conductive via **206** is connected to the electrical circuitry **220** by conventional circuit traces formed in the circuitry **220** itself. The vias **206** thus provide a solid electrical pathway between the Wheatstone bridge circuit of the MEMS pressure sensing element **202** and electrical circuitry **220** formed into the top or first side **216** of the ASIC **204**.

The MEMS pressure sensing element **202** is attached to the ASIC **204** by a bonding layer of silicon dioxide **240**. Input and output signals of the ASIC **204** are available at metal bond pads **223** located on the top side **216** of the ASIC **204**.

FIG. **2B** is a cross-sectional view of a second embodiment of a backside absolute pressure sensor device **200** comprising a MEMS pressure sensing element **202** on top of which is an application specific integrated circuit (ASIC) **204**. The embodiment of FIG. **2B** differs from the one shown in FIG. **2A** by conductive vias **206B** that extend completely through the topside **216** of the ASIC **204**.

As FIG. **2B** shows, the top end **233** of the via **236** is exposed for an electrical connection. Such a via **236** can connect to circuitry **220** formed in the top side of the ASIC **204** and continue to extend upwardly from the circuitry **220** to the top side **216** of the ASIC **204**.

FIG. **3** is a plan view of the first or top side **216** of the ASIC **204** shown in FIG. **2A**. FIG. **3** thus shows in phantom lines four conductive vias **206A-206**D, each of which extend part way up the ASIC **204** from its backside **218**, not visible in FIG. **3**, toward the topside **216** of the ASIC **204**. The vias **206A-206**D are located or positioned in the ASIC to be directly above where metal bond pads **224**A-**224**D are located on the top surface of a MEMS pressure sensing element **202** as shown in FIG. **4** so that the vias **206A-206**D align with the bond pads **224** when the ASIC **204** is placed on top of the MEMS pressure sensing element **202**.

As shown in FIG. **3**, the vias **206**A-**206**D are located along one side **310** of the ASIC **204** but can also be symmetrically distributed around the recess **222** formed into the opposing bottom side **218** of the ASIC **204**, as shown in FIGS. **8**A and **8**B. The location of the recess **222** is depicted in FIG. **3**A as a square drawn in broken or phantom lines. Symmetric distribution of the vias around the recess **222** reduces stress concentrations in the ASIC **204**.

The top side **216** of the ASIC **204** is provided with several metal bond pads **302**, **304**, **306** and **308**. Three of the bond pads **302**, **304** and **306** are denominated as output, ground and input respectively. Five other bond pads **308** are for testing the ASIC **204**.

FIG. **4** depicts the first or top side **208** of the MEMS pressure sensing element **202**. FIG. **4** also depicts the location of four metal bond pads **224**A-**224**D on the top side **208** of the MEMS pressure sensing element **202**.

A Wheatstone bridge circuit is formed by four P− doped piezoresistors **312** near an edge **314** of the diaphragm **212** and four interconnects **316**A-**316**D. The four piezoresistors **312** are electrically connected to the metal bond pads **224**A-**224**D by the four interconnects **316**A-**316**D, which are P+ doped localized regions of the top side **208**.

In the first embodiment of the pressure sensor device **200**, the top side **208** of the MEMS pressure sensing element **202** is attached to the bottom side **218** of the ASIC **204** by a fusion bond. In one embodiment, except for the metal bond pads, the entire top side **208** of the MEMS pressure sensing element **204** is covered with a silicon dioxide layer, which is used to form a silicon fusion bond. In FIG. **4**, a fusion bonding area **318** is provided with a thin layer of silicon dioxide, which when heated provides a silicon fusion bond between the MEMS pressure sensing element **202** and the ASIC **204**. The silicon dioxide **240** in the fusion bonding area **318** can form a silicon fusion bond. In yet another embodiment, also shown by FIG. **4**, the silicon dioxide **240** in the fusion bonding area **318** is additional silicon dioxide placed on top of a layer of silicon dioxide that extends over the entire top surface **208** of the MEMS pressure sensing element **204**. In all three embodiments, an intermetallic bond **230** is formed and located between the conductive vias **206** and metal bond pads **224** as shown in FIG. **2**A or an intermetallic bond **230** is formed and located between the conductive vias **236** and metal bond pads **224** as shown in FIG. **2**B.

In yet other alternate embodiments, the silicon dioxide **240** can be replaced by, or substituted with a layer of glass frit, which when heated bonds the MEMS pressure sensing element **202** to the ASIC **204**. In such embodiments, i.e., where the glass frit covers the top surface **208** or is localized into the fusion bonding area **318**, a small droplet of solder referred to herein as a solder bump is used between the vias **206** and the metal bond pads **224**. The layer of silicon dioxide **240** can also be placed onto the backside of the ASIC **204**.

In yet another embodiment, the cavity/recess above the MEMS pressure sensing element is not evacuated but is instead provided with a fluid having a pressure that is to be sensed, or which is to affect the measurement of a fluid pressure applied to the diaphragm, as required by a differential pressure sensor. In order to apply a fluid pressure into the cavity, a pathway into the cavity must of course be provided.

In order to provide a fluid pathway into the cavity **222**, the layer of either silicon dioxide or glass frit (or a mixture of them) between the ASIC **204** and the MEMS pressure sensing element **202** can be patterned, as shown in FIG. **10**, which shows the top side **1002** of a MEMS pressure sensing element **1000** having a patterned bonding area **1004**. Strips or regions **1006** of either silicon dioxide or glass frit or a mixture of them are separated from each other by spaces **1008** where no silicon dioxides or glass frit is applied to the top side **1002** of the MEMS pressure sensing element **1000**. The open spaces **1008** have a predetermined width **1010** and a height, which extends out of the plane of FIG. **10** by a distance substantially equal to the thickness of the silicon dioxide or glass frit. For air, the thickness of the bonding layer is preferably at least 20 microns up to about 200 microns. The open spaces **1008** are thus sized, shaped and arranged to allow a particular fluid to pass through them and into the recess **222** formed into the second side of the ASIC **204**.

FIG. **5** is a cross-sectional view of a third embodiment of a backside absolute pressure sensor device **500** comprising the MEMS pressure sensing element **202** and the ASIC **204** having conductive vias **206** that extend up from the bottom side **218** of the ASIC **204** part way through the ASIC **204**. The embodiment of FIG. **5** differs from the embodiment shown in FIG. **2-4** by how the ASIC **204** and sensing element **202** are attached to each other.

In the embodiment shown in FIG. **5**, the MEMS pressure sensing element **202** and the ASIC **204** are bonded to each other using a layer of glass frit **502** on the bottom side **218** of the ASIC **204** and a layer of silicon dioxide **504** on the top side **208** of the MEMS pressure sensing element **202**.

FIG. **6** shows another embodiment of a pressure sensor device **600**. The ASIC **204** is attached to the top side of a MEMS pressure sensing element **602**, which has a groove **604** formed into the top side **606** of the element **602**. The groove **604**, which is shown in cross section, surrounds the diaphragm formed into the top side **606** of the MEMS pressure sensing element and collects excess glass frit during the heating required to liquefy the glass frit.

FIG. **7** is a cross-sectional view of the pressure sensor device **200** shown in FIG. **2**A mounted to a pedestal **702**. The pedestal **702** has a top surface **704** and an opposing bottom surface **706**. It also has an aperture **708** that extends all the way through the pedestal **702**. The center **710** of the aperture **708** is aligned with, or at least substantially aligned with the middle of the diaphragm **212** formed in the MEMS pressure sensing element **202**. The pedestal **702** is preferably made of glass or silicon. It isolates the sensing element **202** from surfaces of a housing having thermal expansion coefficients markedly different from the thermal expansion coefficient of the material from which the sensing element **202** is made.

FIG. **8**A is a plan view of an alternate embodiment of an ASIC **800**, the bottom side **802** of which has a recess **804**. FIG. **8**B is a perspective view of the bottom side **802**. One or more trenches **806** are formed into the bottom side **802** of the ASIC **800**. The trenches are narrow and steep-sided cuts or depressions formed into the otherwise substantially planar surface of the bottom side **802** of the ASIC **800**. The trenches **806** extend laterally or sideways through the ASIC **800** from the recess **804** through one of the vertical sides **810** of the ASIC **800**. The trenches are sized and shaped to allow a fluid, the pressure of which is being sensed, to flow into and out of the recess **804** as well as the cavity formed by the recess **804** when the bottom side **802** of the ASIC **800** is attached to the top side of a MEMS pressure sensing element. The trenches **806**, or a patterned bonding layer depicted in FIG. **10**, enable the pressure sensing element to which an ASIC is bonded to provide differential pressure sensing. The trenches **806** preferably pass between conductive vias formed in the ASIC.

FIGS. **8**A and **8**B, which is a perspective view of the bottom side **802**, also show that conductive vias **806** can be symmetrically distributed around the recess **804**, instead of along one side of an ASIC, as shown in FIG. **2**A. In FIGS. **8**A and **8**B, one conductive via **808**A-**808**D is located near each corner of the ASIC **800**. Such vias **808**A-**808**D are thus considered herein to be symmetrically distributed in the ASIC **800**.

FIG. **9** is a plan view of an alternate embodiment of a MEMS pressure sensing element **900** having a distributed Wheatstone bridge circuit formed by four separated piezoresistors **908** and interconnects **906**. Its top surface **902** is provided corner-located metal bond pads **904**A-**904**D, i.e., bond pads located near the corners of the MEMS pressure sensing element **900**. The bond pads **904**A-**904**D are located to align with the symmetrically distributed conductive vias **806**A-**806**D of the ASIC **800** shown in FIG. **8** when the ASIC **800** shown in FIGS. **8**A and **8**B is place on top of the MEMS pressure sensing element **900** shown in FIG. **9**.

Interconnects **906** are formed in the top surface **902** using P+ doping of semiconductor material between the symmetrically distributed bond pads **904**A-**904**D and piezoresistors **908** that are connected to form a Wheatstone bridge. A fusion bonding area **912**, described above with regard to FIG. **4**, surrounds the bond pads **904**A-**904**D and conductive interconnects **906**.

FIG. **11** depicts an alternate embodiment of a backside pressure sensor device **1100** having two integrated circuits stacked on the top of a backside MEMS pressure sensing element. One of the two integrated circuits is preferably an electromagnetic control chip or EMC chip, which reduces or filters electrical noise but which can have other active and/or passive devices.

The embodiment shown in FIG. **11** comprises a backside MEMS pressure sensing element **1102**. As with the MEMS pressure sensing elements described above, the pressure sensing element **1102** shown in FIG. **11** has metal bond pads **1104** on the top surface **1106** of the MEMS pressure sensing element **1102**.

The bond pads **1104** are electrically connected to conductive vias **1108** formed at least part way through a first ASIC **1114**. The vias **1108** extend between circuitry **1118** formed in the top surface **1110** of the ASIC **1114** and the bottom surface **1112** of the ASIC **1114**, An intermetallic bond **1116** is formed between the bond pads **1104** and the vias **1108**.

The vias **1108** connect circuitry **1118** in the top surface **1110** of the ASIC **1114** to the bond pads **1104** and hence connect the circuitry **1118** to a Wheatstone bridge circuit located in the diaphragm **1120** of the MEMS pressure sensing element **1102**.

The diaphragm **1120** is “covered” by an evacuated cavity **1122**. The cavity **1122** is formed from a recess **1122** cut into the bottom surface **1112** of the ASIC **1114** when the ASIC **1114** is attached to the top surface **1106** of the MEMS pressure sensing element **1102**.

The second integrated circuit **1124** is connected to the first integrated circuit **1114** by a second set of conductive vias **1126** formed into the second integrated circuit **1124**. The second set of vias **1126** extend between the top side or surface **1128** and bottom side or surface **1130** of the second integrated circuit **1124**. The second set of vias **1126** go all the way through the second integrated circuit **1124**. As can be seen in FIG. **11**, the vias **1126** are electrically connected to the circuitry **1118** formed in the top side of the first integrated circuit **1114**.

FIG. **12** depicts a first embodiment of a pressure sensor module **1200**. The module **1200** is essentially a pressure sensor device **1202** described above, including at least the one shown in at least FIG. **2**, sealed inside an interior space of a housing **1204**. The pressure sensor device **1202** comprises an ASIC **1214** and a MEMS pressure sensing element **1215**. They are bonded to each other using a fusion bond **1230** described above.

The interior space where the pressure sensor device **1202** is located is referred to herein as a pocket **1206**. A pressure port **1208** is formed through the cover **1205** and leads into the pocket **1206**. The port **1208** is sized and shaped to allow a fluid to flow through the port **1208** and apply pressure to the diaphragm **1218** of the pressure sensor device **1202**.

The pressure sensor device **1202** is mounted to the top side **1216** of the pocket **1206** by an adhesive **1210**. An electrical connection between a lead frame **1222** and bond pads **1220** on the top side **1212** of the ASIC **1214** is provided by an electrically conductive adhesive (ECA) or a solder bump **1228**. The adhesive **1210** is non-conductive and protects the bond pad **1220** as well as the ECA or solder bump **1228**.

FIG. **13** depicts a second embodiment of a pressure sensor module **1300**. The pressure sensor module **1300** of FIG. **13** differs from the pressure sensing module **1200** of FIG. **12** by only the use of a glass fit bond **1302** between the ASIC **1214** and MEMS pressure sensing module **1215**. The glass frit bond is provided by a layer of glass frit between the ASIC **1214** and MEMS pressure sensing module **1215**.

FIG. **14** depicts a differential pressure sensor module **1400**. It differs from the pressure sensor modules shown in FIGS. **12** and **13** by the addition of a trench **1402** formed in the bottom side **1406** of an ASIC **1408**, which allows fluid to enter the cavity **1410** formed by a recess in the bottom side **1406** of the ASIC **1408** and attachment of the ASIC **1408** to the top side **1412** of a MEMS pressure sensing element **1414**.

Unlike the pressure sensor modules described above, the pressure sensor module **1400** shown in FIG. **14** is provided with two pressure ports **1416** and **1418**. A first pressure port **1416** provides a path by which fluid can apply pressure to the backside **1420** of the MEMS pressure sensing element **1414**. An adhesive **1426** attaches the MEMS pressure sensing element **1414** to the cover **1405** and provides a seal around the first pressure port **1416**.

The second pressure port **1418** provides a second and separate path by which a different fluid can apply pressure to the pocket **1422** and the cavity **1410** and hence the top side **1412** of the MEMS pressure sensing element **1414** via the trench **1402**. The pressure sensor module **1400** of FIG. **14** is used for differential pressure sensing while the pressure sensor modules shown in FIGS. **12** and **13** are used for backside absolute pressure sensing.

FIG. **15** depicts another embodiment of a differential pressure sensor module **1500**. It differs from the pressure sensor module **1400** of FIG. **14** by the use of a patterned glass frit **1502** between the ASIC **1408** and MEMS pressure sensing element **1414**. As shown in FIG. **10** and described above, the patterned glass frit **1502** provides a path **1503** for pressurized fluid to flow from the pocket **1422** into the cavity **1410** and exert pressure on the topside of the diaphragm.

FIG. **16** depicts a backside absolute pressure sensor module **1600** comprising a backside absolute pressure sensor device **1602** inside a housing **1613** having a pocket **1606** that encloses the pressure sensor device **1602**. As with the pressure sensor devices described above, the pressure sensor device **1602** depicted in FIG. **16** comprises an ASIC **1604** attached to the top side of a MEMS pressure sensing element **1622**, as described above with respect to at least FIG. **2**A. The ASIC **1604** is attached to the MEMS pressure sensing element **1622** by a fusion bond **1640**, described above.

The ASIC **1604** has metallic bond pads **1608** on the top side **1610** of the ASIC **1604** that are connected by bond wires **1614** to lead frames **1612** that extend through the housing **1613**. The bond wires **1614** are thin and fragile. The bond wires **1614** are therefore protected from breakage by a layer of a viscous gel **1616** that essentially fills the pocket **1606**.

A layer of adhesive **1618** between the bottom **1620** of the backside MEMS pressure sensing element **1622** and the bottom **1624** of the pocket **1606** attaches the MEMS pressure sensing element **1622** to the bottom **1624** of the pocket **1606**. The adhesive **1618** also provides a seal around an aperture **1628** through which a fluid can exert a pressure against the backside **1630** of a diaphragm **1632** formed in the pressure sensing element **1622**. In yet another embodiment, a conformal coating layer is used to hold and protect the bond wire **1614**.

FIG. **17** depicts a second and alternate embodiment of the pressure sensor module **1600** shown in FIG. **16**. The pressure sensor module **1700** shown in FIG. **17** differs from the sensor module **1600** shown in FIG. **16** by only the use of a glass frit **1702** that provides a glass frit bond between the ASIC **1604** and the MEMS pressure sensing element **1622**. The bond wires **1614** are protected by a viscous gel **1616**.

Those of ordinary skill in the art will recognize that the foregoing description is for purposes of illustration only. The true scope of the invention is set forth in the following claims.

What is claimed is:

1. A pressure sensor device comprising:

a MEMS pressure sensing element having first and second sides with a flexible diaphragm and a Wheatstone bridge circuit on the first side;

a first integrated circuit comprising a substrate with first and second sides, electronic circuitry formed into a predetermined portion of the first side and a recess formed into the second side, the second side of the first integrated circuit being attached to the first side of the MEMS pressure sensing element, the recess of the first integrated circuit and the first side of the MEMS pressure sensing element defining a substantially evacuated cavity;

a first plurality of conductive vias formed into the first integrated circuit substrate such that the first plurality of vias extend through the substrate and electrically connect the Wheatstone bridge circuit of the MEMS pressure sensing element to the circuitry formed into the first side of the first integrated circuit; and

at least one of:

i) a layer of silicon dioxide between the first side of the MEMS pressure sensing element and the second side of the first integrated circuit, the layer of silicon dioxide forming a silicon fusion bond between the MEMS pressure sensing element and the integrated circuit; and an intermetallic bond formed between at least one of the conductive vias and an electrical contact on the first side of the MEMS pressure sensing element;

and

ii) a layer of glass frit located between the first side of the MEMS pressure sensing element and the second side of the first integrated circuit, the layer of glass frit forming a bond between the MEMS pressure sensing element and the first integrated circuit; and an electrically conductive protuberance between at least one of the conductive vias and an electrical contact on the first side of the MEMS pressure sensing element.

2. The pressure sensor device of claim **1**, wherein the plurality of conductive vias are symmetrically distributed in the first integrated circuit substrate.

3. The pressure sensor device of claim **1**, further comprising a second integrated circuit attached to the first side of the first integrated circuit, the second integrated circuit comprising a substrate with first and second sides and electronic circuitry formed into a predetermined portion of its first side.

4. The pressure sensor device of claim **3**, further comprising a second plurality of conductive vias formed into the second integrated circuit substrate such that the second plurality of vias extend through the substrate of the second integrated circuit and electrically connect circuitry of the first integrated circuit to circuitry of the second integrated circuit.

5. The pressure sensor of device of claim **1**, further comprising a pedestal attached to the second side of the MEMS pressure sensing element, the pedestal comprising an aperture, which is substantially aligned to the flexible diaphragm.

6. A pressure sensor device comprising:

a MEMS pressure sensing element having first and second sides with a flexible diaphragm and a Wheatstone bridge circuit on the first side;

a first integrated circuit comprising a substrate with first and second sides, electronic circuitry formed into a predetermined portion of the first side and a recess formed into the second side, the second side of the first integrated circuit being attached to the first side of the MEMS pressure sensing element, the recess of the first integrated circuit and the first side of the MEMS pressure sensing element defining a cavity;

a first plurality of conductive vias formed into the first integrated circuit substrate such that the first plurality of vias extend through the substrate and electrically connect the Wheatstone bridge circuit of the MEMS pressure sensing element to the circuitry formed into the first side of the first integrated circuit; and

at least one of:

i) a layer of silicon dioxide between the first side of the MEMS pressure sensing element and the second side of the first integrated circuit, the layer of silicon dioxide forming a silicon fusion bond between the MEMS pressure sensing element and the integrated circuit, the second side further comprising at least one trench formed to extend into the recess; and an intermetallic bond formed between at least one of the conductive vias and an electrical contact on the first side of the MEMS pressure sensing element;

and

ii) a layer of glass frit located between the first side of the MEMS pressure sensing element and the second side of the first integrated circuit, the layer of glass frit forming a bond between the MEMS pressure sensing element and the first integrated circuit; and an electrically conductive protuberance between at least one of the conductive vias and an electrical contact on the first side of the MEMS pressure sensing element, wherein the layer of glass frit is patterned to provide at least one media path through the layer of glass fit, the media path being configured to allow a predetermined fluid to pass through the media path and to the recess formed into the second side of the first integrated circuit.

7. The pressure sensor device of claim **6**, wherein the plurality of conductive vias are symmetrically distributed in the first integrated circuit substrate.

8. The pressure sensor device of claim **6**, further comprising a second integrated circuit attached to the first side of the first integrated circuit, the second integrated circuit comprising a substrate with first and second sides and electronic circuitry formed into a predetermined portion of its first side.

9. The pressure sensor device of claim **8**, further comprising a second plurality of conductive vias formed into the second integrated circuit substrate such that the second plurality of vias extend through the substrate of the second integrated circuit and electrically connect circuitry of the first integrated circuit to circuitry of the second integrated circuit.

10. A pressure sensor module comprising:

a pressure sensor device comprising:

a MEMS pressure sensing element having first and second sides with a flexible diaphragm and a Wheatstone bridge circuit on the first side;

a first integrated circuit comprising a substrate with first and second sides, electronic circuitry formed into a predetermined portion of the first side and a recess formed into the second side, the second side of the first integrated circuit being attached to the first side of the MEMS pressure sensing element, the recess of the first integrated circuit and the first side of the MEMS pressure sensing element defining a substantially evacuated cavity; and

a first plurality of conductive vias formed into the first integrated circuit substrate such that the first plurality of vias extend through the substrate and electrically connect the Wheatstone bridge circuit of the MEMS pressure sensing element to the circuitry formed into the first side of the first integrated circuit;

a housing having a pocket that encloses the pressure sensor device and a pressure port configured to allow a predetermined fluid to apply pressure to the diaphragm; and

a lead frame that extends from an electrical contact on the first side of the first integrated circuit through the housing, the electrical contact on the first side of the first integrated circuit comprising at least one of an electrically conductive protuberance and an electrically conductive adhesive.

11. The pressure sensor module of claim **10**, further comprising a layer of adhesive between the first integrated circuit and an interior surface of the pocket, the layer of adhesive being configured to mount the pressure sensor device to an interior surface of the pocket and substantially cover the electrical contact on the first side of the first integrated circuit.

12. The pressure sensor module of claim **10**, wherein the MEMS pressure sensing element has a plurality of electrical contacts on its first side, the pressure sensor device further comprising:

a layer of silicon dioxide between the first side of the MEMS pressure sensing element and the second side of the first integrated circuit, the layer of silicon dioxide forming a silicon fusion bond between the MEMS pressure sensing element and the first integrated circuit; and

an intermetallic bond formed between at least one of the conductive vias and an electrical contact on the first side of the MEMS pressure sensing element.

13. The pressure sensor module of claim **10**, wherein the MEMS pressure sensing element has a plurality of electrical contacts on its first side, the pressure sensor device further comprising:

a layer of glass frit located between the first side of the MEMS pressure sensing element and the second side of the first integrated circuit, the layer of glass frit forming a bond between the MEMS pressure sensing element and the first integrated circuit; and

an electrically conductive protuberance between at least one of the conductive vias and an electrical contact on the first side of the MEMS pressure sensing element.

14. The pressure sensor module of claim **10**, wherein the plurality of conductive vias are symmetrically distributed in the first integrated circuit substrate.

15. The pressure sensor module of claim **10**, further comprising a second integrated circuit attached to the first side of the first integrated circuit, the second integrated circuit comprising a substrate with first and second sides and electronic circuitry formed into a predetermined portion of its first side.

16. The pressure sensor module of claim **15**, further comprising a second plurality of conductive vias formed into the second integrated circuit substrate such that the second plurality of vias extend through the substrate of the second integrated circuit and electrically connect circuitry of the first integrated circuit to circuitry of the second integrated circuit.

17. The pressure sensor module of claim **10**, further comprising a pedestal attached to the second side of the MEMS pressure sensing element, the pedestal comprising an aperture, which is substantially aligned to the flexible diaphragm.

18. A pressure sensor module comprising:

a pressure sensor device comprising:

a MEMS pressure sensing element having first and second sides with a flexible diaphragm and a Wheatstone bridge circuit on the first side;

a first integrated circuit comprising a substrate with first and second sides, electronic circuitry formed into a predetermined portion of the first side and a recess formed into the second side, the second side of the first integrated circuit being attached to the first side of the MEMS pressure sensing element, the recess of the first integrated circuit and the first side of the MEMS pressure sensing element defining a substantially evacuated cavity; and

a first plurality of conductive vias formed into the first integrated circuit substrate such that the first plurality of vias extend through the substrate and electrically connect the Wheatstone bridge circuit of the MEMS pressure sensing element to the circuitry formed into the first side of the first integrated circuit; and

at least one of:

i) a layer of silicon dioxide between the first side of the MEMS pressure sensing element and the second side of the first integrated circuit, the layer of silicon dioxide forming a silicon fusion bond between the MEMS pressure sensing element and the integrated circuit; and an intermetallic bond formed between at least one of the conductive vias and an electrical contact on the first side of the MEMS pressure sensing element;

and

ii) a layer of glass frit located between the first side of the MEMS pressure sensing element and the second side of the first integrated circuit, the layer of glass frit forming a bond between the MEMS pressure sensing element and the first integrated circuit; and an electrically conductive protuberance between at least one of the conductive vias and an electrical contact on the first side of the MEMS pressure sensing element;

a housing having a pocket that encloses the pressure sensing device and a pressure port configured to allow a predetermined fluid to apply pressure to the diaphragm;

a lead frame that extends from inside the pocket through the housing;

a bond wire that extends from an electrical contact on the first side of the first integrated circuit to the lead frame; and

an adhesive layer located between the second side of the MEMS pressure sensing element and an interior surface of the pocket through which the pressure port is formed, the adhesive layer surrounding and sealing the pressure port to the second side of the MEMS pressure sensing element.

19. The pressure sensor module of claim **18**, further comprising a layer of gel inside the pocket and substantially covering the pressure sensor device.

20. The pressure sensor module of claim **18**, further comprising a conformal coating over the pressure sensor device, the bond wire and at least part of the lead frame.

21. The pressure sensor module of claim **18**, wherein the plurality of conductive vias are symmetrically distributed in the first integrated circuit substrate.

22. The pressure sensor module of claim **18**, further comprising a second integrated circuit attached to the first side of the first integrated circuit, the second integrated circuit comprising a substrate with first and second sides and electronic circuitry formed into a predetermined portion of its first side.

23. The pressure sensor module of claim **22**, further comprising a second plurality of conductive vias formed into the second integrated circuit substrate such that the second plurality of vias extend through the substrate of the second integrated circuit and electrically connect circuitry of the first integrated circuit to circuitry of the second integrated circuit.

24. The pressure sensor module of claim **18**, further comprising a pedestal attached to the second side of the MEMS pressure sensing element, the pedestal comprising an aperture, which is substantially aligned to the flexible diaphragm.

25. A pressure sensor module comprising:

a pressure sensor device comprising:

a MEMS pressure sensing element having first and second sides with a flexible diaphragm and a Wheatstone bridge circuit on the first side;

a first integrated circuit comprising a substrate with first and second sides, electronic circuitry formed into a predetermined portion of the first side and a recess formed into the second side, the second side of the first integrated circuit being attached to the first side of the MEMS pressure sensing element, the recess of the first integrated circuit and the first side of the MEMS pressure sensing element defining a cavity;

a first plurality of conductive vias formed into the first integrated circuit substrate such that the first plurality of vias extend through the substrate and electrically connect the Wheatstone bridge circuit of the MEMS pressure sensing element to the circuitry formed into the first side of the first integrated circuit; and

at least one of:

i) a layer of silicon dioxide between the first side of the MEMS pressure sensing element and the second side of the first integrated circuit, the layer of silicon dioxide forming a silicon fusion bond between the MEMS pressure sensing element and the integrated circuit, the second side further comprising at least one trench formed to extend into the recess; and an intermetallic bond formed between at least one of the conductive vias and an electrical contact on the first side of the MEMS pressure sensing element;

and

ii) a layer of glass frit located between the first side of the MEMS pressure sensing element and the second side of the first integrated circuit, the layer of glass frit forming a bond between the MEMS pressure sensing element and the first integrated circuit; and an electrically conductive protuberance between at least one of the conductive vias and an electrical contact on the first side of the MEMS pressure sensing element wherein the layer of glass frit is patterned to provide at least one media path through the layer of glass frit, the media path being configured to allow a predetermined fluid to pass through the media path and to the recess formed into the second side of the first integrated circuit;

a housing having a pocket that encloses the pressure sensing device and a pressure port configured to allow a predetermined fluid to apply pressure to the diaphragm;

a lead frame that extends from inside the pocket through the housing;

a bond wire that extends from an electrical contact on the first side of the first integrated circuit to the lead frame; and

an adhesive layer located between the second side of the MEMS pressure sensing element and an interior surface of the pocket through which the pressure port is formed, the adhesive layer surrounding and sealing the pressure port to the second side of the MEMS pressure sensing element.

26. The pressure sensor module of claim **25**, wherein the plurality of conductive vias are symmetrically distributed in the first integrated circuit substrate.

27. The pressure sensor module of claim **25**, further comprising a second integrated circuit attached to the first side of the first integrated circuit, the second integrated circuit comprising a substrate with first and second sides and electronic circuitry formed into a predetermined portion of its first side.

28. The pressure sensor module of claim **27**, further comprising a second plurality of conductive vias formed into the second integrated circuit substrate such that the second plurality of vias extend through the substrate of the second integrated circuit and electrically connect circuitry of the first integrated circuit to circuitry of the second integrated circuit.

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